Heterogeneous Integration of Silicon and Printed Electronics for Intelligent Sensing Devices

LI XIE

Doctoral Thesis
Information and Communication Technology
Electronic Systems
Stockholm, Sweden 2014
Driven by the exploding popularity of the Internet-of-Things (IoT), the demand for thin, flexible, lightweight intelligent sensing devices is growing rapidly. Two attractive examples are intelligent packaging and wearable healthcare monitoring devices, which help to connect and track/monitor everything/everybody at any time and in any place. The remarkably swift development of flexible and printed electronics is promoting new possibilities for cost-effective manufacturing of such devices. However, compared with silicon-based circuits, state-of-the-art all-printed circuits are encountering low integration density, long switching time and corresponding high cost per function. Therefore, a heterogeneous platform is in great demand, which employs a cost-effective, large-area manufacturing technique while keeping the same complex functionality and processing capability as silicon-based systems. Due to temperature and mechanical reasons, traditional silicon integration methods, such as solder bonding and wire bonding, are not suitable for flexible printed electronics. This thesis aims to develop a generally applicable heterogeneous integration platform for the realization of intelligent sensing devices on flexible substrates.

First, inkjet printing technique is introduced and studied. As the basic and key element, inkjet printing technology is employed to fabricate interconnections as well as electrodes of the printed sensors. Novel flexible media, plastic and paper, are evaluated as the substrates of printed electronic systems from two aspects: the electrical characteristics and performance reliability. In addition to widely used inkjet/photo paper, packaging paper is presented as a promising candidate for intelligent packaging applications due to the advantages in terms of lower price, higher temperature endurance and better reliability against 85 °C/85% RH aging.

Second, the heterogeneous integration platform enabled by inkjet printing is presented. Benefiting from the non-contact, accurate alignment and fine resolution features, this integration technique has the advantages of simplified fabrication process and multi-substrate compatibility. The design rules have been studied and the integration process is optimized for silicon chips with/without packaging.

Finally, to verify the suitability, the heterogeneous integration platform is applied to two representative applications, each with unique emphasis and requirements.

For intelligent packaging, low-cost is one crucial requirement. Paper substrate is selected because it is cost-effective, recyclable and a commonly-used packaging material in industry. In order to fit into non-regular shape packages, the intelligent packaging needs to be bent or folded, which brings about reliability concern for paper electronics. Therefore, bending and folding tests are applied to reveal the capability and the limitation of paper electronics in terms of flexibility. For applications such as fresh food tracking, humidity is an important physical quantity to monitor during transportation and...
storage. Therefore, a resistive humidity sensor based on multi-walled carbon nanotubes is fabricated and integrated. A commercial packaged microcontroller is used to sense and store the resistance of the sensor and control the LEDs to indicate the ambient humidity level. By integrating the microcontroller, LEDs and a switch with the printed sensor and battery, a prototype of a paper-based humidity sensor card is implemented.

For the healthcare application, user comfort is an essential element. Future long-term healthcare devices require a bio-sensing system which is small, thin, lightweight and wearable, has a long-battery life, and is easy to customize. The heterogeneous platform offers a promising solution for such systems from three aspects. 1) A fully integrated system-on-chip (SoC) is embedded to detect and process the bio-signal. The SoC solution features tiny size and low-power consumption, which contribute to system miniaturization and long battery lifetime. 2) Inkjet printing offers a cost-effective approach to fabricate personalized electrodes. 3) Inkjet printed interconnections enable the direct integration of the bare die instead of the packaged chip. This significantly reduces the physical size of the system, simplifies the manufacture process and lowers the cost. The concept is demonstrated by a miniaturized wearable Bio-Patch with the size of 4.5 cm × 2.5 cm.

**Keywords:** Intelligent Packaging, Wearable Healthcare Device, Heterogeneous Integration, Inkjet Printing technology, System-on-Chip, f-MWCNTs Humidity Sensor, Bio-Signal Sensor.
Acknowledgements

This thesis would never become a reality without the help and support of people surrounding me, both at work and in private. I would like to express my sincere gratitude to:

Prof. Li-Rong Zheng, my supervisor, for giving me the opportunity to join iPack and introducing me to the field of printed electronics. His uplifting perspective and creative ideas always inspire me throughout my research.

Dr. Qiang Chen, my co-supervisor, for the support to my Ph.D studies and the valuable suggestions both professional and personal.

Dr. Fredrik Jonsson for guiding me to the projects and teaching me circuit and system design. Prof. Axel Jantsch for his kind help and practical advice. Prof. Ahmed Hemani for reviewing the thesis.

The administrative staff and the IT support group for their assistance in all kinds of issues.

All the co-authors for their cooperation and contribution. Special thanks to: Dr. Matti Mäntisalo for his professional guidance, constructive suggestion and continuous encouragement; Dr. Yang Geng for thoughtful advice, constant help and enormous support; Feng Yi for her earnest work manner, pleasant friendship and the insightful discussion about the research as well as life. Without any of you, I would not have achieved such progress.

All my colleagues at iPack and ES for creating a pleasant working environment. Special thanks to: Shen Jue, my officemate, for the valuable memories at work and after work; Liu Ming, Liu Pei and Liu Shaoteng, for your company since my first day to Sweden; and all the friends who helped me with the experiments and who made the lunch time something to look forward to. They are too many to mention, I thank you all.

My badminton group members, for the happy and healthy hours every Saturday afternoon. Your company brought color to my life in Stockholm.

My dear friends both in Sweden and China, for all the happy moments that we spent together, and for the encouragement which keeps me positive when facing the difficulties.

Gunhild Shah, my roommate, for taking care of my life like real family.

Thanks to Prof. Donald Lupo for being my opponent; Prof. Smail Tedjini, Prof. Bengt Olemann, and Prof. Richard Uusijärvi for being committee members.

Finally, I wish to express my gratitude to my husband Qijiang for understanding, support and patience; my parents, sister and brother-in-law for always being there.

Li Xie
November 2013
Stockholm
List of Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFE</td>
<td>Analog Front-End</td>
</tr>
<tr>
<td>ACA</td>
<td>Anisotropic Conductive Adhesive</td>
</tr>
<tr>
<td>ACF</td>
<td>Anisotropic Conductive Film</td>
</tr>
<tr>
<td>ACP</td>
<td>Anisotropic Conductive Paste</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotube</td>
</tr>
<tr>
<td>CMRR</td>
<td>Common Mode Rejection Ratio</td>
</tr>
<tr>
<td>DP</td>
<td>Drop Spacing</td>
</tr>
<tr>
<td>$D_{p,\text{max}}$</td>
<td>Maximum drop spacing</td>
</tr>
<tr>
<td>$D_{p,\text{opt}}$</td>
<td>Optimum drop spacing</td>
</tr>
<tr>
<td>DS</td>
<td>Drop Size</td>
</tr>
<tr>
<td>ECA</td>
<td>Electrical Conductive Adhesive</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>EEG</td>
<td>Electroencephalogram</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyogram</td>
</tr>
<tr>
<td>EOG</td>
<td>Electrooculograms</td>
</tr>
<tr>
<td>f-MWCNT</td>
<td>Functionalized Multi-Walled Carbon Nanotube</td>
</tr>
<tr>
<td>FPE</td>
<td>Flexible and Printed Electronics</td>
</tr>
<tr>
<td>GR&amp;R</td>
<td>Gauge Reproducibility and Repeatability</td>
</tr>
<tr>
<td>ICA</td>
<td>Isotropic Conductive Adhesive</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IDE</td>
<td>InterDigital Electrodes</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
</tr>
<tr>
<td>MWCNT</td>
<td>Multi-Walled Carbon Nanotube</td>
</tr>
<tr>
<td>NCA</td>
<td>Non-Conductive Adhesive</td>
</tr>
<tr>
<td>NPS-JL</td>
<td>Nano-Particle Silver Jetable Low-temperature</td>
</tr>
<tr>
<td>OLED</td>
<td>Organic Light-Emitting Diode</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PE</td>
<td>Printed Electronics</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene Terephthalate</td>
</tr>
<tr>
<td>PEN</td>
<td>Polyethylene Naphthalate</td>
</tr>
<tr>
<td>PHA</td>
<td>Personal Health Assistant</td>
</tr>
<tr>
<td>PI</td>
<td>Polyimide</td>
</tr>
<tr>
<td>QFN</td>
<td>Quad Flat No-Lead</td>
</tr>
<tr>
<td>R2R</td>
<td>Roll-to-Roll</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency IDentification</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Sheet Resistance</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SoC</td>
<td>System-on-Chip</td>
</tr>
<tr>
<td>SpikeE</td>
<td>Spiked Electrodes</td>
</tr>
<tr>
<td>SWCNT</td>
<td>Single-Walled Carbon Nanotube</td>
</tr>
<tr>
<td>TAB</td>
<td>Tape Automated Bonding</td>
</tr>
<tr>
<td>TFT</td>
<td>Thin Film Transistor</td>
</tr>
<tr>
<td>TextE</td>
<td>Textile-based Electrodes</td>
</tr>
</tbody>
</table>
Publications

List of papers included in this thesis:

I Electrical Performance and Reliability Evaluation of Inkjet-Printed Ag Interconnections on Paper Substrates


*The author’s contribution:* planning and performing the experiments, evaluation of the results and writing the main parts of the manuscript.

II Heterogeneous Integration of Bio-Sensing System-on-Chip and Printed Electronics


*The author’s contribution:* planning and performing the main parts of experiments, evaluation of the results and writing the main parts of the manuscript.

III Integration of f-MWCNTs Sensor and Printed Circuits on Paper Substrate


*The author’s contribution:* planning and performing the main parts of experiments, evaluation of the results and writing the main parts of the manuscript.

IV Bio-Patch Design and Implementation Based on a Low-Power System-on-Chip and Paper-based Inkjet Printing Technology


*The author’s contribution:* planning and performing parts of the experiments and writing parts of the manuscript.

V A Hybrid Low Power Bio-Patch for Body Surface Potential Measurement


*The author’s contribution:* planning and performing parts of the experiments and writing parts of the manuscript.
VI A System-On-Chip and Paper-Based Inkjet Printed Electrodes for a Hybrid Wearable Bio-Sensing System


*The author’s contribution:* planning and performing the main parts of experiments, evaluation of the results and writing the main parts of the manuscript.

VII Characterization of Dry Biopotential Electrodes


*The author’s contribution:* planning and performing the main parts of experiments, evaluation of the results and writing the main parts of the manuscript.
List of related papers not included in this thesis:

I Integration of Intelligent Packaging, Unobtrusive Bio-Sensors and iMedBox, towards Pervasive Health-IoT Service
Geng Yang, Li Xie, Matti Mäntysalo, Xiao-Lin Zhou, Zhi-Bo Pang, Li Da Xu, Sharon Kao-Walter, Qiang Chen and Li-Rong Zheng, IEEE Transactions on Industrial Informatics, accepted, 2014.

II Intelligent Tag-System for Mass Customization and Smart Warehouse with the Internet of Things
Jue Shen, Li Xie, Jia Mao, Zhi-Bo Pang, Zhuo Zou, Li-Rong Zheng, and Hannu Tenhunen, IEEE Transactions on Industrial Informatics, under revision, 2014.

III Wireless Interconnections for Paper Electronics
Li Xie, Yi Feng, Geng Yang, Botao Shao, Qiang Chen and Li-Rong Zheng, IEEE Microwave and Wireless Components Letters, manuscript.

IV Evaluation of non-contact flexible electrodes connected with a customized IC-steps towards a fully integrated ECG sensor
Geng Yang, Li Xie and Li-Rong Zheng, IEEE NORCHIP, 2013.

V A Passive UHF-RFID Tag with Inkjet-Printed Electrochromic Paper Display
Jue Shen, Li Xie, Jia Mao and Li-Rong Zheng, IEEE International Conference on RFID, 2013.

VI Co-Design of Flip Chip Interconnection with Anisotropic Conductive Adhesives and Inkjet-Printed Circuits for Paper-Based RFID Tags
Li Xie, Jue Shen, Jia Mao, Fredrik Jonsson and Li-Rong Zheng, IEEE 61st Electronic Components and Technology Conference (ECTC), 2011.

VII Inkjet Printing in System Integration - Printed Humidity Sensor-Box
Li Xie, Matti Mäntysalo, Fredrik Jonsson, Yi Feng, Ana Lopez Cabezaz and Li-Rong Zheng, 11th Flexible Electronics and Displays Conference (FlexTech), 2012.

VIII System Integration of Smart Packages using Printed Electronics
Matti Mäntysalo, Li Xie, Fredrik Jonsson, Yi Feng, Ana Lopez Cabezaz and Li-Rong Zheng, IEEE 62st Electronic Components and Technology Conference (ECTC), 2012.

IX Fabrication and Performance Evaluation of Ultralow-Cost Inkjet-Printed Chipless RFID Tag
Yi Feng, Li Xie, Ana Lopez Cabezas, Maik Muller, Matti Mäntysalo, Fredrik Forsberg, Qiang Chen, Li-Rong Zheng and Werner Zapka, *Large-area, Organic & Printed Electronics (LOPE-C)*, 2012.

X Intelligent Packaging with Inkjet-Printed Electrochromic Paper Display - A Passive Display Infotag


XI Integration of Bio-Patch and Imedbox for IN-HOME Healthcare and Services

Geng Yang, Li Xie, Zhi-Bo Pang, Qiang Chen and Li-Rong Zheng *Medicinteknikdagarna*, 2013, Stockholm.
Contents

1 Introduction 1

2 Inkjet-Printed Interconnections 7
   2.1 Introduction of Inkjet Printing Technology . . . . . . . . . . . . . . . 7
   2.2 Flexible Substrates: Plastic vs Paper . . . . . . . . . . . . . . . . . . 9
   2.3 Experimental Setup and Process Optimization . . . . . . . . . . . . . 11
   2.4 Performances of Printed Interconnects . . . . . . . . . . . . . . . . . 15

3 Heterogeneous Integration Platform 19
   3.1 Traditional Chip-to-Package/Substrate Integration . . . . . . . . . . . . 19
   3.2 Silicon-on-Flex Enabled by Inkjet Printing . . . . . . . . . . . . . . . 24

4 Flexible Intelligent Packaging 31
   4.1 Intelligent Packaging and Paper Electronics . . . . . . . . . . . . . . . 31
   4.2 Fatigue of Interconnects versus Bending and Folding . . . . . . . . . . . 33
   4.3 f-MWCNT Humidity Sensor . . . . . . . . . . . . . . . . . . . . . . . 35
   4.4 Demonstration: Humidity Sensor Card . . . . . . . . . . . . . . . . . 37

5 Wearable Healthcare Monitoring Devices 39
   5.1 Bio-Potential Signals and Customized SoC . . . . . . . . . . . . . . . 39
   5.2 The ECG Signal . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
   5.3 Dry Electrodes . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
   5.4 Demonstration: Miniaturized Wearable Bio-Patch . . . . . . . . . . . . 45

6 Summary and Future Outlook 49

Bibliography 51
Chapter 1

Introduction

The Internet of Things (IoT) is a vision of ‘everything connectivity’: for anybody and anything, at anytime and from anyplace [1]. The IoT extends current Internet to the real physical world (things and objects), and has been recognized as the third wave of the Information and Communication Technology (ICT) industry [2]. IoT is bringing about a revolution in logistics, distribution industries and daily lives. As the vital building blocks of IoT, smart objects are required to be aware of and interactive with the environment [3], build a network through wireless links and bridge them to existing ICT infrastructures [4]. IoT requires technical innovation in fields from sensors to nanotechnology to make objects smart and small [2].

As the microelectronics and nanoelectronics kept on making electronic systems smaller and smaller, a new dimension with the principle of ‘bigger can be better’ was proposed and has attracted tremendous attention, as so-called macroelectronics [5] or large area electronics [6]. Initially, macroelectronics was driven by area-intensive applications, such as displays and photovoltaics. Then, the application scope has expanded dramatically over recent decades, covering medical, sensing, flexible and ultrathin consumer devices, pursuing cheaper electronics capable of interacting with the environment on the macroscale [6]. The development of Flexible and Printed Electronics (FPE) enables the cost-effective manufacture of such devices.

Combining the achievements of traditional graphic printing technologies, electronics and materials, the third printing revolution is coming [7], referred as Printed Electronics (PE). Generally speaking, PE means printing circuits on media, such as plastics [8], textiles [9] and papers [10]. With the development of printable functional inks, including conductors, semiconductors, dielectrics, electrochromic and etc, several traditional printing techniques have been adopted to the manufacture of PE, such as gravure, flexographic, offset, screen and inkjet printing, as shown in Fig.1.1. Recently, the FPE has been rapidly developed driven by the promise of low-cost, high-volume, high-throughput production of electronic devices which are lightweight and small, thin and flexible, inexpensive and disposable. Such devices cover a broad range of application fields, including displays [11], sensors [12, 13],
antennae [14, 15], transistors [16, 17], etc. As predicted, the market of FPE will grow rapidly with the annually increase of over 27% reaching US$1B in 2020 [18].

For state-of-the-art thin film transistors (TFTs), the mobility is up to 100 cm$^2$/V·s with the dimensions of tens of micrometers, which is sufficient for some applications such as display drivers [19]. However, the electrical performance is still not comparable with silicon-based transistors, the mobility of which is up to 1500 cm$^2$/V·s with a dimension of nanometers. The fully printed circuits still face the problems of slow response time and low integration density [20], and are not ready for mass production of intelligent objects which require complex functionality and processing capability. Fully printed electronics are on the way but not coming soon [21, 22]. Instead of acting as the substitute or competition of silicon-based electronics, PE provides new possibilities and features to macroelectronics. The complementariness of silicon-electronics and printed electronics is shown in Fig.1.2.

Figure 1.1: Three elements of printed electronics. Figures from Internet.

Figure 1.2: Complementariness of printing electronics and silicon-electronics. Courtesy: Institute of Print and Media Technology, Chemnitz University of Technology.
As declared by R.H. Reuss, ‘the rapid commercialization and adoption of macro-electronics ultimately depends on cost and performance metrics for the given application’. Therefore, a heterogeneous system is in strong demand to combine the high-performance silicon-electronics and cost-effective printed electronics and fill the technological gap between fully-printed electronics and the expansive market of the intelligent objects.

One attractive application is ubiquitous intelligent packaging for logistics or retailing, which enables the connection of ‘anything’. One example of such flexible heterogeneous system is shown in Fig.1.3. The printed large-area devices and traditional silicon circuits are seamlessly integrated on the flexible substrate. With these functional blocks, smart packages can sense the ambient, display numbers/images, interact with the end-user, process data, and exchange commands and the information with the internet through the wireless network. With the intelligent packages, the state of the products can be identified and realtime-monitored during the whole life-cycle, including production, packaging, transportation, retail, and finally recycling.

Another emerging application is personalized and pervasive healthcare, which enables the seamless-connection of ‘anybody’. An E-Healthcare system based on a wearable bio-sensing device (Bio-Patch) and IoT is illustrated in Fig.1.4 with an application scenario of bio-signal monitoring. The Bio-Patch detects the bio-signals from the site where it is placed. These bio-signals are converted into a digital format and wirelessly transmitted to a smart phone or personal health assistant (PHA) for storage or real-time processing/display. According to the requirements, the data can also be sent to a remote server or hospital/clinic center for storage, where a further diagnosis can be made by the remote physicians. In case of an emergency, an alarm can automatically be sent to the emergency center requesting urgent medical help. In order to apply long-term real-time bio-signal monitoring, the Bio-Patch should be worn all-day-long, which makes user-comfort an essential requirement. Future healthcare devices would require systems which are small, thin, lightweight,
wearable, long-battery life, and easy customization. The heterogeneous platform provides new possibilities for such systems.

Figure 1.4: The structure of an E-Healthcare monitoring system based on a wearable bio-sensing device (Bio-Patch).

Compared with the traditional packages or copper-clad boards for electronic systems, the features of printed circuits on flexible substrates present new challenges to the integration techniques as well as the system design, especially for low-cost substrates such as polyester (PET) and paper.

- First, the maximum temperature that flexible substrates can stand is rather low, e.g. between 110-150 °C for many types of paper and PET [23]. This makes it impossible to use traditional technology such as solder bonding.
- Second, the substrate is soft and fragile, and the adhesion between the printed layers and the substrate is not as strong as the copper-clad and traditional circuit boards. Therefore high pressure should be avoided [24].
- Third, the printed interconnects using sintered nano-particle metal inks on flexible substrates are lossy with high resistance compared with bulk metal traces on conventional copper-clad boards. Therefore, classic models or equations are not suitable anymore, and new electrical characteristics are required for system design.

Based on these considerations, this thesis aims to develop a heterogeneous integration platform for System-on-Flex and intelligent devices. This thesis is a combination of multidisciplinary research work that crosses system design, printed electronics, biomedical and humidity sensors, with the main emphasis being on endowing the devices with intelligence by embedding sensors, enduring emerging features to electronic systems by integrating silicon-based electronics with flexible printed electronics, proposing new solutions for system implementation, enriching functionality and expanding applications of daily objects. The thesis is structured as follows: Chapter 2 introduces the basics of inkjet printing technology and the experimental setup. Chapter 3 presents the heterogeneous integration platform for flexible electronic systems and the relevant performance evaluation. The application determines the selection of substrates, inks, components and functional devices,
which in turn presents challenges to system integration. To evaluate the suitability and generality of the proposed platform, two typical intelligent sensing devices have been implemented: intelligent packaging and a wearable bio-sensing device, which are presented in Chapters 4 and 5 respectively. Chapter 6 summarizes the thesis and suggests a future outlook.
Chapter 2

Inkjet-Printed Interconnections

Printing technologies are under rapid development as promising manufacture approaches for the low-cost, high-volume, high-throughput production of flexible intelligent devices [10]. Among all current printing techniques, inkjet printing technology has several unique features. This chapter first gives an overall introduction about inkjet printing technology. Then, the different substrates are introduced, followed by the experimental setup and process optimization. Finally, the electrical characteristics of printed interconnects are evaluated.

2.1 Introduction of Inkjet Printing Technology

Nowadays, lots of traditional printing technologies have been adopted to fabricate electronic systems, including gravure, flexographic, offset, screen, inkjet printing, etc. Each printing technique has a unique process, and therefore presents specific performances, such as resolution, thickness, homogeneity, printing speed, required printing pressure, ink and substrate properties [10, 7]. Table 2.1 lists some typical parameters [10]. The selection of which technique to use should depend on the requirements of the particular application.

As a digital printing technique, inkjet printing has attracted enormous attention as an approach to deposit functional inks. The improvement of jettable functional inks has enabled the manufacture of RFID tags, flexible displays, thin film transistors and various sensors. According to the electrical property, the inks can be divided into three categories: dielectrical inks, semiconductive inks and conductive inks [10].

Conductive inks are always the basic elements for all types of electronics [25, 26]. Both organic and inorganic materials can be used to make conductive inks. When the conductivity requirement is not strict, the conducting organic materials, such as conducting polymers [27], CNTs [28] and graphite [29], are preferred due to the low cost, flexibility, simple processing, and in some cases transparency. While metal-based inks should be selected for applications with high requirements of the
CHAPTER 2. INKJET-PRINTED INTERCONNECTIONS

Table 2.1: Comparison of common printing techniques [10].

<table>
<thead>
<tr>
<th>Printing Technique</th>
<th>Print Resolution $\mu$m</th>
<th>Print Speed $\text{m/min}$</th>
<th>Wet Film Thickness $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexo</td>
<td>30-70</td>
<td>50-500</td>
<td>0.5-8</td>
</tr>
<tr>
<td>Gravure</td>
<td>20-75</td>
<td>20-1000</td>
<td>0.1-5</td>
</tr>
<tr>
<td>Offset</td>
<td>20-50</td>
<td>15-1000</td>
<td>0.5-2</td>
</tr>
<tr>
<td>Screen</td>
<td>50-100</td>
<td>10-100</td>
<td>3-100</td>
</tr>
<tr>
<td>Inkjet</td>
<td>1-50$^{\dagger}$</td>
<td>1-100</td>
<td>0.3-20</td>
</tr>
</tbody>
</table>

$^{\dagger}$ The printing resolution and speed depend on several factors, including nozzle diameter, drop spacing, and number of nozzles. There is a trade-off between printing resolution and speed.

---

Figure 2.1: The inkjet-printing process of conductive pattern manufacture using metal-nanoparticle inks.

stability and conductivity [30]. An additional advantage for metal-based inks is the possibility to be recycled by de-inking [10].

Taking the manufacture of conductive patterns using silver nano-particle ink as an example, the inkjet-printing process includes two basic steps:

Firstly, deposit drops of ink on the substrate when the digital image requires, as shown in Fig. 2.1a. Besides common features such as Roll-to-Roll (R2R) compatibility large-scale and high volume, the inkjet printing technique $^{1}$ has unique features including digital, additive, non-contact, mask free, print-on-demand, high resolution and accurate alignment. These features in turn enable the following advantages:

- Easy and cost-effective to customize the printing pattern.

---

$^{1}$Fundamentally, there are two sorts of inkjet printing: the continuous jetting and the drop-on-demand jetting, and each sort has several categories according to different drop deflection/formation methodologies [31]. Nowadays, most of the printers on the market are the thermal/piezoelectric drop-on-demand printers, and ‘inkjet print’ means ‘drop-on-demand’ inkjet in this thesis.
2.2 Flexible Substrates: Plastic vs Paper

Polyimide (PI) is one of the most popular substrates for flexible printed electronics. In the experiments, a commercially available PI foil (Kapton 500HN, DuPont) is used because of its smooth surface, chemical and moisture resistance, low shrinkage behavior, and high thermal durability up to 400 °C. The electrical performance, mechanical performance, and reliability have been evaluated[36, 25, 26]. One example of printed patterns on PI is shown in Fig.2.2a. However, there are concerns regarding its price and the impact on environment.

Polyethylene, polypropylene and PET are the top-three most produced polymers and are commonly used in packaging. They are considered as low cost substitutes of PI for FPE. One example of PET-based printed patterns is shown in Fig.2.2b. However, the drawback is the lack of ability to stand high temperature [10]. The thermal expansion coefficient is large (60-200 ppm K⁻¹) which leads to deformation when heated. The glass transition temperature of PET is only 70 °C. This limits the application where high annealing temperature is needed.

Secondly, evaporate the dispersion solvent, sinter the metallic particles and form conductive lines/films, as shown in Fig.2.1b. There are various sintering methods, including laser [32], pulsed light [33], microwave [34], electricity [35], etc. Although the process is time-consuming, the conventional oven sintering is still the most reliable sintering method for silver nano-particle inks [30].

![Polyimide](a) Polyimide  ![PET](b) PET  ![Paper](c) Paper

Figure 2.2: Printed conductive patterns on flexible substrates.
Paper, as the cheapest and most widely used flexible and recyclable substrate in everyday life so far, is therefore considered to be a potential alternative substrate for printed electronics [37, 38, 39]. One example of printed patterns is shown in Fig. 2.2c. However, there are concerns regarding paper-based electronics. First, the properties of paper substrates not only depend on the composition and structure of papers, but also vary in different environment [10]. Second, the relevant research is mainly based on photo paper, which is relatively expensive. Third, water molecules can be easily absorbed into the cellulose fibers that paper is usually made of [40], which will present challenges to applications, such as intelligent packaging in fresh food tracking.

With the increasing demand for intelligent packaging, companies are beginning to consider the possibility of directly integrating the printed system onto packages of commercial products [21]. Using package paper as the substrate of electronic systems makes it possible to merge the manufacture of electronics into normal package fabrication processes and thereby reduce the manufacturing steps and further lower the cost. In addition, package paper is designed for good resistance against environmental variations compared with office and photo paper. Therefore, package paper is of great interest to realize paper electronics. As samples, six papers from two typical categories (inkjet paper and package paper) were studied in Paper I as the printing substrate. The detailed characteristics are listed in Table 2.2.

Table 2.2: Characteristics of six paper substrates and morphology of relative inkjet-printed dots and lines. Figure adapted from Paper I.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Thickness</th>
<th>Maximum Temperature</th>
<th>Dot</th>
<th>Drop Size</th>
<th>Drop Spacing</th>
<th>1 Pixel Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inkjet Paper¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kodak</td>
<td>250 µm</td>
<td>120 °C</td>
<td>28 µm</td>
<td>20 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schoeller²</td>
<td>290 µm</td>
<td>100 °C</td>
<td>28 µm</td>
<td>20 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEL</td>
<td>220 µm</td>
<td>150 °C</td>
<td>28 µm</td>
<td>20 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Paper³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV</td>
<td>420 µm</td>
<td>180 °C</td>
<td>40 µm</td>
<td>35 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PE</td>
<td>470 µm</td>
<td>120 °C</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>520 µm</td>
<td>140 °C</td>
<td>65 µm</td>
<td>46 µm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Inkjet papers are named after the company names.
² Commercial photo paper
³ Package papers are provided by Korsnäs AB. They are named after the coating material.
Figure 2.3: a) Dimatix Materials Printer (DMP2800). b) Firing drops from nozzles. c) Printed drops and d) single line on Substrates.

2.3 Experimental Setup and Process Optimization

Printing Setup

The samples were printed on a DMP-2800 printer (Fujifilm Dimatix materials printer shown in Fig.2.3a) with printhead DMC-11610 (drop volume of 10 pl). Nano-Particle Silver Jetable Low-temperature ink (NPS-JL) from Harima Chemicals Inc. is selected because of the low sintering temperature. The recommended sintering temperature condition is 120-150 °C for 60 min. The specific resistance is 4-6 µΩ·cm with a thickness of around 1µm after curing. By setting the suitable waveform and dropping parameters, the firing drop formation (Fig.2.3b) could be obtained, and landed on the substrate forming regular dots (Fig.2.3c) and lines (Fig.2.3d).

Printing Resolution Selection

Different substrates have different surface characteristics (e.g. surface energy, roughness, porosity), which influence the ink-surface interactions and lead to different dot shapes and drop sizes. Therefore, for different substrates, even printing using the same ink with the same printing parameters, the drop size and line width will be different, which influences the printing resolution. The relationship between the printed line width (W), drop size (DS) and drop spacing (DP) is shown in Fig.2.4.

The examples of printed lines with different print resolutions are shown in Fig.2.4a [41]. The DP decreases from the left image to the right one. Extremely large DP leads to the isolated printed dots. As the DP decreases, continuous even lines are formed. If the DP is too small, bulges will appear. The suitable DP should be selected meticulously according to different DS.
The maximum drop spacing $D_{\text{P(\text{max})}}$ to form a continuous line is equal to $DS$. For this setting, two adjacent dots are barely connected as shown in Fig. 2.4b. The resolution of this printed pattern is low, and less nano-particle ink is needed. However, the printed pattern faces a high risk of open circuits. Meanwhile, since there is very little ink per unit area, the sintered silver film is thin which leads to large sheet resistance. As the DP decreases, the resolution increases, and the sheet resistance decreases, but it consumes more ink. Therefore, there is a trade-off between the performance and the price. Based on this consideration, the optimum drop spacing $D_{\text{P(opt)}}$ shown in Fig. 2.4c is recommended. The $D_{\text{P(opt)}}$ calculated by Equation 2.1 ensures that the diagonal dots are tangential and the adjacent dots are well connected.

$$D_{\text{P(opt)}} = DS/\sqrt{2}$$

In order to select the optimized printing parameters for each substrate, a $10 \times 10$ dot matrix was printed firstly. The average drop size was measured and the optimal drop spacing was calculated respectively. Printed lines are another basic element that determines the quality and limitation of printed pattern due to ink-substrate interactions. Hence 1 pixel lines were also printed on each substrate. The printed dots and lines on the selected six paper substrates were examined by an optical microscope and shown in Table 2.2.

![Images of inkjet-printed lines with decreasing Drop Spacing](image)

b) Maximum Drop Spacing
c) Optimum Drop Spacing

Figure 2.4: a) Examples of printed lines with decreasing drop spacing [41]. The relationship of drop size ($DS$), drop spacing ($DP$) and line width ($W$) for the case of b) maximum drop spacing and c) optimum drop spacing.


2.3. EXPERIMENTAL SETUP AND PROCESS OPTIMIZATION

![Four-point measurement diagram](image)

Figure 2.5: Four-point measurement. a) 4-point structure, apply the current through the outer pair of electrodes and measure the voltage from the inner pair of electrodes. b) and c) Measurement setup using homemade PCB-based measurement set.

**Four-Point Measurement**

In order to evaluate the electrical performance of printed interconnects, a four point measuring technique is applied for resistance (R) measurement. The four-point structure is shown in Fig.2.5a. By applying the four-point method, the current and voltage electrodes are separated, and as a result, the impedance contribution of the wiring and contact resistances can be eliminated. The sheet resistance ($R_s$) is calculated by Equation 2.2.

$$R_s = \frac{R}{L/W}$$  \hspace{1cm} (2.2)

A homemade PCB-based measurement set (Fig.2.5b) is manufactured to ensure the repeatability and reliability of the measurement. Spring contacts are used to ensure a good contact with the four pads simultaneously. Labview is used to control the Agilent 34401A multimeter and record the data. For each single resistance measurement, the mean value out of 10 times measurement is recorded to minimize the variation caused by the measurement setup. Fig.2.5c shows the photograph of a real measurement.

Each sample includes 25 structures to evaluate the distribution. The gauge reproducibility and repeatability (GR&R) method is used to evaluate the measurement error due to the device and the operator [42]. Five different set-ups for resistance measurement are chosen to complete the GR&R, the value of which varies from one another and covers the whole value range. Three operators are chosen to apply the GR&R measurements. All of them complete each part three times in a randomly arranged sequence. Analysis of Variance (ANOVA) is used as the data assessing method. The analysis indicates,

1. Different ranges of resistance values can be clearly distinguished from each other.
2. The effect of operators is ignorable.
CHAPTER 2. INKJET-PRINTED INTERCONNECTIONS

3. The resolution of the measurement system is 0.049 Ω, which means the system cannot distinguish smaller differences.

4. The measurement error caused by the measurement system and the operator is 2.5%, below 4%, the requirement for a good measurement system.

Samples for Rs measurement were designed and fabricated using the optimal inkjet printing parameters for individual substrate. Each sample includes 25 four-point structures for a standard deviation analysis. We evaluate sheet resistance instead of resistivity because 1) it can be directly and accurately measured; 2) it is the combination result of influence factors, such as the substrate and ink material, the influence of substrate-ink interaction, and the printing process and setting; 3) it is the direct electrical parameter to be used in the final circuit design, 4) the exact thickness or cross-sectional area of printed structures on paper substrate is difficult to measure because: first, the roughness of paper substrate is not ignorable; second, the absorption of the ink deforms the paper substrate.

Optimization of Nano-Particle Sintering Temperature

Many low-cost substrates, such as PET and paper, limit the annealing temperature of printed inks up to 150 °C. In order to evaluate the influence of the sintering temperature on the electrical performance of printed wires, the four-point measurement samples on PEL paper were sintered in an oven at 100 °C, 120 °C and 150 °C for 1 hour, respectively. As shown in Fig.2.6, from 120 °C to 150 °C, the Rs decreased considerably by 50 %, while from 100 °C to 120 °C, the improvement is not significant.

![Figure 2.6](image)

Figure 2.6: The distribution of sheet resistance of inkjet printed interconnects on PEL with sintering condition of 100 °C, 120 °C and 150 °C for 1 hour. Each test group includes 25 four-point structures. *Figure adapted from Paper III.*
2.4 Performances of Printed Interconnects

Electrical Characteristics

According to the parameters listed in Table 2.2, four-point measurement structures were printed on these six paper substrates and sintered at 100 °C for 1 hour. $R_s$ of each sample was measured and the morphology was characterized using a high resolution scanning electron microscope (HRSEM, Zeiss Ultra 55). Fig. 2.8 shows...
the box plot of the $R_s$ and the respective SEM pictures. Based on Table 2.2 and Fig.2.8, the following phenomena are observed:

1. Inkjet papers feature smooth surface, good ink control and absorption, and high dimensional stability. Therefore, inkjet papers have less $R_s$ and standard deviation than package papers.

2. Among the other inkjet papers, PEL is specially designed for nano-particle inks and features small pore size (around 60 nm) therefore it shows the best conductivity and repeatability.

3. Silver nano-particles are absorbed into the bulk of Clay paper along with the ink solvent, so the printed patterns are dark instead of normal metallic color.

4. The printed dots and lines on PE paper have irregular edges, which indicates that PE paper is not suitable for inkjet printing of fine patterns. There are silver grains exist on top of PE paper, where the printed pattern presents a metallic color. However, the SEM picture indicates that there are clear gaps between the silver grains, so no conductivity is gained.

5. Regular and clear edges of dots and lines are formed on UV paper. Therefore it is suitable for fine-pattern printing. UV paper has a higher surface energy and smaller contact angle than inkjet papers, so larger dots are formed. Therefore, larger drop spacing is selected for UV paper, which contributes to greater $R_s$ than inkjet papers. The variation of $R_s$ on UV paper is also greater. One possible reason is the coating on UV paper is not as homogeneous as inkjet papers because of its much cheaper coating process. However, the $R_s$ is still acceptable for various applications.
In brief, surface characteristics of paper substrates (e.g., porosity, surface roughness and absorption rate) depend very much on the coating material and coating process, which influence how the ink diffuses, the drying and sintering process, and thereby determine the electrical performance of printed interconnects. A more detailed description is presented in Paper I.

Reliability Evaluation in an 85 °C/85% RH ambient environment

Considering the application of intelligent packaging, the reliability of paper-based electronics in a high moisture and high temperature environment is very important. In order to evaluate the performance, an ageing test was applied on paper-based samples according to the industry standard [43]. Four-point measurement samples on PEL paper and UV paper were put into an environmental chamber (WK11-180, Weiss Tecknik) with the test condition set at 85 °C/85% RH and a total testing time of 1008 hours (six weeks). The $R_s$ measurement was repeated once per week to track the variation. The variation for the initial sintering temperatures of 90 °C, 120 °C and 150 °C follow the same tendency, and the results of 90 °C are plotted in Fig. 2.9 with the SEM pictures of samples after Week 6.

A large reduction of $R_s$ happened during the first week, and then the value becomes rather stable during the following weeks. This indicates that silver nanoparticles may continue being sintered in an 85 °C /85% RH environment until it reaches the stable state, as evidenced by larger silver grains in the SEM pictures than in Fig. 2.8.

During Week 1 to 3, the printed interconnects on both substrates showed good reliability. From Week 4, 4 out of 25 interconnects on PEL paper broke, while only one interconnect on UV paper exhibited abnormally high resistance one week later. After the 6-week ageing test, the PEL paper became slightly yellow, curly and stiff, while the UV paper still kept its original looks.

These results verify that the printed interconnections on inkjet papers show

![Figure 2.9: The variation of sheet resistance ($R_s$) during the ageing test for inkjet printed Ag lines on a) PEL with b) SEM picture after Week 6, and on c) UV with d) SEM picture after Week 6. Figure adapted from Paper I.](image-url)
smaller sheet resistance and better repeatability than those on package papers. However, low-cost package paper has higher resistance against environmental variation than the inkjet paper. Package paper is suitable for intelligent package applications which are price-sensitive, have less strict requirements on conductivity and high demands on moisture resistance. More discussions are presented in Paper I.
Chapter 3

Heterogeneous Integration Platform

Fully printed electronics is still at an early stage of development and is not ready for mass production of intelligent devices [21, 22, 44]. Meanwhile, following the Moore’s Law, with the continuous scaling down of semiconductor technology, the silicon chip efficiently merges high performance RF/digital/analog circuit blocks and enables huge data processing ability for the sensing and interactive functionality [45]. Therefore, heterogeneous systems are proposed to take advantage of both silicon-based circuits and printed electronics. The features of printed circuits on flexible substrates present new challenges to the integration techniques. In this chapter, the heterogeneous integration technologies are discussed.

3.1 Traditional Chip-to-Package/Substrate Integration

Wire Interconnections

The development of silicon chips has spawned modern advanced electronics such as smart phones and the personal digital assistants [46]. The Chip-to-Package/Substrate integration enables the silicon chip to be electrically interconnected to the package and the other embedded user-interfaces, e.g. displays, sensors and keyboards. Three primary interconnection techniques are widely used to realize the integration, including wire bonding, tape automated bonding (TAB), and flip chip bonding, as shown in Fig.3.1.

Wire bonding connects pads on the chip to the package using fine gold, aluminum or copper [47] lines with thermosonic or ultrasonic welding methods. Wire bonding is cheap, reliable and flexible with the changing of chip/package pattern [48]. The metallized lead frame on the package is required to stand bonding temperatures of 150-200 °C with a bonding force of around 100 g [46]. Jerald presented a fabric-based screen-printed system integrating chips using wire-bonding as shown
in Fig.3.2 [49]. However, small metal beams are actually used as the chip-carrier on soft fabrics to stand the required pressure, which means extra processing and cost. In addition, concerns arise regarding the influence of yield, reliability and performance.

TAB mounts the chips to a metallized flexible polymer tape. The principle involves creating tiny AuSn eutectic intermetallic compounds, using a heated thermode under certain pressure, at the chip-lead interface to form the metallurgical bond. TAB was proposed as a low-cost substitution of wire-bonding due to its reel-to-reel compatibility, and it is able to handle high-density fine-pitch chips. However, because of process inflexibility and large capital equipment investment, it received little industry acceptance for electronic packaging [46].

With flip-chip bonding, chips are directly attached on substrates face-down. The electrical interconnections are formed using solder bumps or conductive adhesives. The advantages include highly improved costs, reliability, productivity, electrical performance and packaging density [50]. Solder interconnects are commonly used for microprocessors. However, the process temperature should be higher than 200°C due to the melting points of the bump material [46]. Meanwhile, since conductive adhesives were first patented in the 1950s [51], electrical conductive ad-

Figure 3.1: Chip-to-Package/Substrate interconnection techniques [46].

Figure 3.2: The modified wirebonding process for chip integration on fabric-based screen-printed systems [49].
hesives (ECA) have been intensively developed for flip-chip integration \[52, 53\]. As a promising alternative to traditional solders, ECA is more environmentally friendly and overcomes technical problems of solders \[54, 55, 53\].

According to the conductive principle and direction, the ECA could be divided into two classifications: isotropic conductive adhesives (ICA) and anisotropic conductive adhesives (ACA). For ICA, the electrical conductivity is formed by the adhesive itself, so that it is conductive in all directions. For ACA, the glue is not conductive in itself and the electrical connection is established through contacting the conductive particles distributed within the glue. Therefore, the ACA only conduct in one direction. ACA are normally offered in two forms, i.e. paste (ACP) or film (ACF). The schematic diagrams of assembly processes for these ECAs are shown in Fig.3.3.

The features of ECA make it possible to be used for flexible electronics integration, and several groups have presented their investigation on it. Vyas et al. demonstrated a wireless sensor transmitter on a paper substrate integrating discrete components with an inkjet-printed antenna using ICA shown in Fig.3.4a \[56\]. New materials for ICA have also been presented for electronic packaging applications \[57\]. However, unlike solders, ICAs cannot self-align during the assembly, so a higher precision assembly process and slower assembly tools are required \[46\]. The spread of ICA may cause a short-circuit between adjacent interconnects, and this limits its application for small-pitch chips or bare dies.

While for ACA, thermo-compression bonding is normally used for the assembly. Under the pressure and heat, the non-conductive glue shrinks and forms a stable mechanical connection to fasten the location of the chip and the substrate. Meanwhile, the conductive particles in ACA are deformed and form the electrical connection paths between the bumps on the chip and the substrate metallization.

![Figure 3.3: The schematic diagrams of assembly process for a) the isotropic conductive adhesive (ICA), b) the anisotropic conductive paste (ACP), and c) the anisotropic conductive film (ACF).](image-url)
CHAPTER 3. HETEROGENEOUS INTEGRATION PLATFORM

It is worth mentioning that the electrical conductivity only works vertically and the short-circuit is efficiently prevented as long as the particle size and the metal contents are within a safety range compared with the pad size and the pitch. For micro-size particles, ACA can be used for bare-die integration with a pad size as small as 40 \( \mu \text{m} \) [58] and space as small as 20 \( \mu \text{m} \) [59] on glass [59], plastic substrate [60] and even paper [61]. One example is shown in Fig.3.4b [59].

Utilizing the ECA-enabled integration approach, two prototypes for healthcare monitoring have been implemented.

Prototype-A is a single-channel body surface potential measurement device as shown in Fig.3.5a. The bio-electric chip was integrated with printed circuits on a photopaper substrate using ICA. The paper substrate is selected due to its potential of cost-efficiency and recyclability. The bio-electric chip is mounted onto the prototype using a socket and therefore it is easy to get reused. A flat Enfucell battery is utilized because it is light, thin and flexible. The total size of Prototype-A is 6 cm \( \times \) 8 cm with operational duration of up to 2 months.

However, as we noticed, the package (JLCC84 with the physical size of 3 cm \( \times \) 3 cm) for the bio-chip is the bottleneck and it limits the miniaturization of the Bio-Patch. In addition, the rigid nature of JLCC84 package reduces the flexibility of Prototype-A and makes it not so comfortable for the user to wear. Therefore, Prototype-B is designed directly integrating the bare-silicon bio-chip with the printed circuits. Instead of ICA, ACA is utilized for system integration since it is suitable for fine pitch applications and it offers good flexibility against bending [58]. A fineplacer pico ma is used to place the chip and provide the pressure and heat for thermo-compression bonding. Polyimide is used as the substrate of Prototype-B to withstand the curing temperature and pressure. The total size of the Prototype-B is 16 cm \( \times \) 16 cm with a thickness of less than 1.5 mm with the use of an Enfucell soft battery.

More detailed description and results about these two prototypes are presented in Papers IV and V.
3.1. TRADITIONAL CHIP-TO-PACKAGE/SUBSTRATE INTEGRATION

Wireless Interconnections

With the scaling down of the technology, the CMOS integration density and clock frequency increase and the on-chip structure size decreases. This brings high demands for high-density high-performance interconnections. However, limited by the fundamental material characteristics, it is hard for the wire interconnects to follow the scaling trend and this becomes the bottleneck of the whole electronic system [62, 63]. To overcome this limitation, wireless interconnects are proposed as a revolutionary solution for both inter- and intra-chip integration [64].

The wireless interconnect system is composed of three blocks: transmitter, receiver and wireless channel. One possible solution is the optical interconnect [65, 66]. However, it requires special optical devices and channels which are not easy to integrate with CMOS IC and circuit boards. Meanwhile, by communicating through electromagnetic waves, the RF-wireless interconnects can achieve the propagation speed of the light while eliminating specific devices. The high propagation speed indicates the interconnect delay could be highly reduced. By using a proper transmission scheme, it is possible for multiple transceivers to share the same channel. In addition, it is easy to distribute global signals [67].

Nowadays, two transmission schemes are mainly presented. One is based on on-chip antennas as shown in Fig.3.6 for both intra-chip and inter-chip communication [68, 69]. 15 GHz global clock signal was transmitted with a distance of 5.6 mm. Using a binary phase-shift-keying impulse radio signal, a high data rate of 200 Mb/s with an inter-chip channel length of 20 cm was achieved [62].

Another scheme is proximity interconnects based on capacitive or inductive coupling as shown in Fig.3.7 [63, 70]. In order to gain large capacitance or mutual inductance, the effective distance for proximity interconnects is limited. Capacitive coupling implies low power consumption, but the two chips need to be placed face-
to-face within a short micrometer distance. In addition, it is sensitive to alignment. Inductive coupling allows longer-distance multi-chips communication and it has a less strict co-planarity requirement. However, the transceiver circuits are more complicated with higher power consumption.

The wireless interconnections propose a potential solution for flexible printed electronics, especially paper electronics, because they do not require a high bonding temperature and pressure used by the traditional integration approach. With the use of advanced RF communication technology, multiple I/O channels can share the same interconnection and therefore balance the size difference between the small-scale silicon chip and the large-scale printed off-chip structures.

### 3.2 Silicon-on-Flex Enabled by Inkjet Printing

ACA offers a possible solution to Silicon-on-Flex integration. However, the assembly process requires high-accuracy placement followed by a high force bonding tool.
3.2. **SILICON-ON-FLEX ENABLED BY INKJET PRINTING**

with high degree of planarity, and the typical bonding forces are 20-100 g per bump, which limits the number of I/O of the chip [46]. The pressure required may cause problems for pressure-sensitive components and fragile substrates. In addition, the process temperature of commercially available ACA with fine pitch capability (minimum pitch around 100 µm) is normally above 160 °C \(^1\), which influences the application for low-temperature substrates.

Therefore, a heterogeneous integration platform enabled by inkjet printing technology is presented. The integration process is shown in Fig.3.8 including four steps: 1) dispense Non-conductive adhesive (NCA); 2) place component with contact-part upwards and cure NCA; 3) inkjet print circuit pattern as well as interconnections; 4) sinter.

![Integration Process Diagram](image)

**Figure 3.8: Heterogeneous system integration using inkjet printing technology. Adapted from Paper II.**

The NCA plays an important role with two key functionalities: a) it forms a stable and strong mechanical connection between the components and the flexible substrate; b) it evens out the height gap between the components and the substrate with a smooth NCA ramp.

The thickness of commercial packaged chips, e.g. QFN, is around 1 mm. This height gap is large considering the small injected drop volume (1-10 pl depending on the cartridges). Therefore, the shape of the NCA ramp is critical. For bare dies, the thickness is lower, down to less than 250 µm, which makes the integration easier. However, the pad size of the bare die is only tens of micrometers with the pitch in the same level. Compared with packaged chips (hundreds of micrometers), the pad

\(^1\)Refers to the production datasheets from companies: Dexerials, HitachiChemical, and 3M.
size of bare dies means more critical requirements on the alignment accuracy and printing resolution. Nevertheless, this integration method has proved to be suitable for both cases and two successful examples are shown in Fig. 3.9.

Compared with the traditional manufacture and assembly process of PCB-based electronic systems, the inkjet-print-enabled heterogeneous integration platform has the following advantages:

- The printing of chip-to-flex interconnects can be manufactured in the same process with the circuit pattern. Therefore, the manufacture is simplified with a reduced number of process phases.
- Inkjet printing is non-contact and the interconnection material is the same as the other circuit pattern. Therefore, no special requirements for the integration process in terms of pressure and temperature. This makes this integration approach suitable for all the substrates compatible with printed electronics.
- By modifying the process setting, the inkjet printing technique is capable of printing a wide range of interconnects, from several micrometers to larger than hundreds of micrometers. This makes it flexible to integrate bare dies as well as packaged chips.

**Geometry Design Rule**

In order to improve the resolution and accuracy of inkjet printed interconnects and fit to small pads, narrow lines with well-controlled width are preferred \[71\]. However, the available line width (W) is discrete and determined by drop size and drop spacing, while the drop size is highly influenced by ink-substrate interfaces, as mentioned in Chapter 2. Two substrates are involved for heterogeneous interconnections: PI and NCA. In order to get the design rule, a set of lines with the width of 1 pixel to 5 pixels are printed on both surfaces. The surface is treated using a fluorine-based chemical EGC-1720 to control the contact angle and obtain a small drop size and line width. The printheads of both 10 pl and 1 pl are tested with a

![Figure 3.9: Examples of inkjet printed interconnections for a) packaged chip integration, and bare die integration for b) top view, c) side view.](image)
3.2. SILICON-ON-FLEX ENABLED BY INKJET PRINTING

Figure 3.10: The width of inkjet printed interconnects with 1-5 pixels by 1 pl and 10 pl printheads on PI and NCA. Figure adapted from Paper II.

calculated DP\(_\text{opt}\) of 30 \(\mu\text{m}\) and 14 \(\mu\text{m}\) respectively. Since the edge of the printed lines is not uniform, and in order to eliminate short connections between adjacent lines, the maximum width of printed lines for each case is measured as shown in Fig.3.10. The results indicate that:

1. With the same printing setting, printed interconnects on PI are wider than on NCA ramp.
2. 10 pl printhead manufactures lines two times larger than 1 pl printhead. Therefore a 10 pl printhead is suitable for large-area pattern printing or interconnection printing to integrate packaged chips, while a 1 pl printhead is preferred for fine interconnect printing for bare die integration.
3. 3-pixel lines are suitable for integrating silicon chips with the pad size of 65 \(\mu\text{m}\) \(\times\) 65 \(\mu\text{m}\) and the pitch size of 90 \(\mu\text{m}\).

**Electrical Performance of Printed Interconnects**

The resistance (R) of lines could be calculated by Equation 3.1

\[
R = \rho \times \frac{L}{W \times T}
\]

(3.1)

where L, W and T are the length, width and thickness of the lines respectively and \(\rho\) is the resistivity. The thickness of single-layer printed interconnects is around 1 \(\mu\text{m}\) and the width is in the scale of tens of micrometers, while the resistivity is rather large compared with the bulk metal. Therefore, the heterogeneous interconnects may induce large serial resistance. Increasing printing layers is one
CHAPTER 3. HETEROGENEOUS INTEGRATION PLATFORM

Figure 3.11: The width and Sheet Resistance of inkjet printed interconnects on PI with 1-5 pixel and 1-5 printing layers. A 1 pl printhead is used. Adapted from Paper II.

potential solution to reducing the serial resistance by increasing the line thickness. Multi-layer printing could also reduce the possibility of an open circuit caused by discontinuities of the substrate/NCA ramp surface. However, multi-layer printing will cause an ink overflow and increase the risk of short circuits between adjacent interconnects, so there is a trade-off. In order to quantitatively evaluate the influence of printing layers, 1-5 pixel lines are printed on PI for 1-5 layers, and the line width is plotted in Fig.3.11. The sheet resistance is also measured using the four-point measurement setup introduced in Chapter 2 and the results are shown in the same figure. The results indicate that:

1. The line width increases linearly with the increase of printing layers.
2. Sheet resistance decreases monotonously with the increase in printing layers, but the descend speed slows down.
3. More printing layers are preferable in order to ensure good electrical connection. However, the layer number is limited by the pad geometry. There is a trade-off between the performance and the short-circuit risk. Different pixels and print layers should be used for specific applications.

Reliability Evaluation of Heterogeneous Interconnects

For flexible electronics, the reliability against bending is one important parameter. The bending test indicates that the inkjet-printed conductive wires on polymer substrate provides good tolerance against bending [72]. However, the reliability may be affected for printed heterogeneous interconnects because it involves a nonplanar surface and 3 different surfaces (pads on chip, NCA ramp and PI substrate). Therefore, three samples with different structures are implemented as shown in Fig.3.12a for a static bending test.
The samples are bent around cylinders with decreasing radii and the resistance of the samples are recorded. The resistance variation of the samples is plotted in Fig.3.12b. The resistance for all three samples increases when bent, while Sample III encountered the largest variation. However, for bending radii as small as 3.5 mm, the maximum variation is still less than 4%, which is safely negligible for many cases. In addition, the resistance recovers when the samples are released. No obvious metal crack or peel-off was noticed after tens of repetitive bending cycles. The bending test indicates that printed electronics on PI can work reliably for lots of applications such as healthcare devices and intelligent packaging. In order to improve the reliability and protect the conductive circuits against the environment, a thin layer of dielectric material could be added on top of the printed electronics as insulation and protection. More detailed results and discussion about the heterogeneous integration platform are presented in Paper II.

Figure 3.12: a) Samples for static bending test. b) Resistance variation of the samples as a function of bending radii. $R_{flat}$ refer to resistance measured when the sample is flat before bending, and $R_{br}$ means resistance at one specific bending radius.
Chapter 4

Flexible Intelligent Packaging

The integration of sensors makes the packages ‘intelligent’ to sense, interact and inform [3]. Intelligent packaging, as an indispensable component of the Internet of Things, is bringing a revolution in logistics, distribution industries and everyday lives [2]. In this chapter, the heterogeneous integration platform is applied for an intelligent packaging application, and a prototype of paper-based sensor system is implemented by integrating f-MWCNTs-based humidity sensor, silicon chip, and printed interconnections. The limitation of paper electronics caused by bending and folding is evaluated, and the guideline to design paper-based intelligent packaging is presented.

4.1 Intelligent Packaging and Paper Electronics

Intelligent is defined as ‘incorporating a microprocessor and having its own processing capability’ and ‘able to vary its state or action in response to varying situations and past experience’ according to the Oxford Dictionary. Intelligent packaging, also called smart packaging or clever packaging, refers to a packaging system which contains an indicator and is capable of applying intelligent functions for product quality determination, in order to extend shelf-life, improve safety, provide information and warn about possible dangers [73, 74]. Relevant functions include detecting, sensing, recording, tracing, communicating, and calculating [74]. The starting point of intelligent packaging is surveillance in the supply chain and logistics [21], including the monitoring of environment (e.g., temperature, humidity or gas) and security (e.g., intrusion or sealing), and item-level tracking and identifications during storage or transportation [75]. Two smart packaging systems are shown in Fig.4.1 with the application scenarios of moisture and intrusion monitoring.

The packaging business is price-sensitive, which restricts the selection of the materials and manufacturing process [23]. The ‘inform and interact’ functionality of intelligent packaging requires the use of large-area devices, such as sensors, displays, batteries, and antennae [44]. Therefore, an efficient system-integration
approach is required. In addition, each package for a particular product has a unique design, and therefore the intelligent packaging should be easy and cheap to be customized. As stated in previous chapters, the inkjet printing technique provides a cost-effective solution for both circuit printing and system integration in both large- and small-volume production. Therefore, it is promising for intelligent packaging manufacturing.

At the meanwhile, enabled by printed electronics and functional inks, paper is considered to be an attractive substrate for electronics, named ‘Paper Electronics’ [10]. Because paper is ubiquitous, cost-effective, light, flexible and recyclable, it is considered to be an outstanding substrate for intelligent packaging. Bending or folding is required to fit paper electronics into non-regular shaped packages for storage and transportation [38]. However, there is a common concern for paper electronics regarding the electrical reliability versus bending and folding, which may limit the performance and system design. Some foldable or bendable paper-based systems were presented in [38, 37, 77] as shown in Fig.4.2. However, drawbacks still exist. The bendable antenna in Fig.4.2a [37] is implemented by a conductive pen, which is not suitable for high volume production. The gas sensor tag in Fig.4.2b is inkjet printed on paper substrate [77], but a statistic analysis of the influence of bending on the performance is missing. In [38], authors had a overall discussion

Figure 4.1: Examples of RFID-based smart packaging. a) Printed moisture monitoring system [76]. Intrusion monitoring system with b) the electronics embedded inside corrugated board package and c) sealing tape at the outside [21].

Figure 4.2: Examples of bendable or foldable paper-based systems. a) A 3D antenna [37]. b) A gas sensor tag [77]. c) An origami crane with LED eyes, and d) an electronic envelope [38].
4.2 Fatigue of Interconnects versus Bending and Folding

Figure 4.3: Schematic diagram of the bending test when the sample is a) flat, b) bent with metal on the outside (Cond-Up), and c) bent with metal on the inside (Cond-Down).

Figure 4.4: The SEM pictures of printed wires after a) Cond-Down bending, b) Cond-Down bending with the surface metal layer peeled off, c) Cond-Up bending, and d) zoom in figure of the crack part in c).

about printed circuit boards on paper and presented some foldable systems shown in Fig. 4.2c and d. However, the fabrication method has drawbacks of poor precision. As to inkjet printed circuits, the reliability against bending and folding is interesting and important for the intelligent packaging application.

4.2 Fatigue of Interconnects versus Bending and Folding

Non-organic coated inkjet paper (PEL from Printed Electronics Ltd.) is used as the paper substrate. A DMP2800 printer is used to jet NPS-JL ink on PEL to print test samples. Each sample includes 8 four-point structures with a length of 2 cm and width around 1.3 mm. According to the discussion in Chapter 2, the sintering condition is set at 100 °C for 1 hour.

The bending test was applied by attaching samples to the cylinders with different radii. There are two different ways to bend the sample: one is with metal on the outside (Cond-Up bending in Fig. 4.3b), and another is with metal on the inside (Cond-Down bending in Fig. 4.3c). Cond-Up bending adds tensile stress to the metal layer while Cond-Down bending induces compressive stress [38]. Different stresses will cause different cracks in the thin metal layers and results in different reliability performance against bending. Therefore, both ways were tested, and the microstructures of bent wires were examined using a High Resolution Scanning Electro Microscope (HRSEM, Zeiss Ultra 55), as shown in Fig. 4.4. The resistance was recorded for each bending radius.
Figure 4.5: Schematic diagram of folding test when the sample is a) flat, b) folded to angle $\theta$ with metal on the outside (Cond-Up), and c) folded to angle $\theta$ with metal on the inside (Cond-Down).

Figure 4.6: The SEM pictures of printed wires after a) Cond-Down folding, b) Cond-Up folding. Figure adapted from Paper III.

The folding test was applied by folding the samples from $0^\circ$ (flat in Fig.4.5a) to $180^\circ$ (totally folded) with Cond-Up (Fig.4.5b) and Cond-Down (Fig.4.5c). The broken samples were examined by HRSEM and the SEM pictures were shown in Fig.4.6. The resistance was recorded for folding angles in $30^\circ$ increments.

The variation of measured conductance of printed wires when bent and folded are plotted in Fig.4.7, from which the following conclusions have been observed:

1. The reliability of paper electronics against bending and folding is different with the metal layer on the inside (Cond-Down) or outside (Cond-Up) of the package, because of the different failure mechanisms: compressive stress for Cond-Down while tensile stress for Cond-Up.
2. Printed wires withstand smaller bending radii when Cond-Down (1 cm) than Cond-Up (2 cm).
3. Printed wires withstand larger folding angle when Cond-Down ($120^\circ$) than Cond-Up ($60^\circ$).
4. $90^\circ$ folding is the most common case for the package boxes. For such applications, it would be preferable to assemble the printed electronics on the inner side of the package.

More detailed results and discussion are presented in Paper III.
4.3 F-MWCNT Humidity Sensor

Humidity sensors are popular and much needed for versatile applications such as smart packaging, fresh food tracking, and environmental control [78, 79]. Traditional resistive-type humidity sensors are mainly made out of oxide ceramics and polymers [78]. However, oxide ceramics are rigid and brittle, and polymers have the drawbacks of low sensitivity, slow response and poor stability [80, 81]. Compared with these materials, carbon nanotubes (CNTs) are attracting enormous research interest as a promising sensing material due to their high flexibility and mechanical strength [82], printability [83] and good thermal and electrical conductivity [84]. A resistive humidity sensor on polymer substrate based on the multi-walled carbon nanotubes functionalized by acid-treatment (F-MWCNTs) was realized and gained excellent sensitivity and fast response to changes in the ambient humidity level [80, 85, 86].

Sample Fabrication

With the aid of inkjet printing and spray coating, a f-MWCNTs humidity sensor on a paper substrate was implemented following in the following steps:

1. Prepare f-MWCNTs solution [80]. The raw MWCNT powders (Sigma-Aldrich Ltd.) were functionalized by acid treatment in a mixture of concentrated H2SO4 and HNO3 in a 3:1 ratio in volume for 24 hours. These functionalized MWCNTs (f-MWCNTs) were then re-dispersed in de-ionized water after the acid residues were washed off. The functional groups (i.e. carboxylic groups) introduced onto the nanotube surface by the treatment both facilitate the solubility of MWCNTs in water and improve the sensitivity of MWCNTs towards humidity [87].
2. Print electrodes. The interdigital structure was used as the electrodes (IDEs) pattern to provide large contact area with the CNTs and the ambient [88]. The IDEs were fabricated by inkjet printing with the same setting with the printed wires, as shown in Fig.4.8a and the schematic electrode in Fig.4.8b.

3. Spray-coat f-MWCNTs and cure. Spray coating is considered to be a good choice to develop large-area, pin-hole free films with a uniform thickness [89, 90]. A modified spray coating system was used to deposit the f-MWCNT solution on the printed IDEs, the illustration of which is shown in Fig.4.9. The nitrogen brings the f-MWCNT solution from the container to the nozzle. When passing through the nozzle, the solution is atomized and the small droplets are deposited on the pre-fabricated IDEs. A hot plate is used to heat the substrate during the deposition so that the droplets could dry fast and avoid forming inhomogeneous film. The sample is then cured in an oven at 100 °C until the resistance remains stable.

An example of the humidity sensor is shown in Fig.4.8c. The paper-based humidity sensors show a similar phenomenon while carrying out the same bending and folding tests. Cond-Down bending/folding leads to smaller conductance variation than Cond-Up bending/folding. Paper-based sensors show less reliability than polymer-based ones reported in [80], which means that the flexibility is limited by the paper substrate. The reliability of the humidity sensor against bending is not as good as printed interconnects, which indicates that the spraying and drying process of f-MWCNT solution undermines the overall flexibility. The folding of the paper-based humidity sensor in either case should be avoided since a large variation (30%) happened for 90° Cond-Down folding and became fully broken for 90° Cond-Up folding. More results and discussion are reported in Paper III.

**Humidity Sensibility Test**

An environmental chamber (WK11-180, Weiss Tecknik) was used to provide different relative humidity (RH) levels and temperatures. The static sensibility test
4.4 Demonstration: Humidity Sensor Card

A paper-based humidity sensor card was developed as the demonstration of intelligent packaging as shown in Fig.4.11. A commercial microcontroller (MCU), a push-button, LEDs, an Enfucell soft battery were integrated with inkjet printed circuits and the humidity sensor on a paper substrate. The heterogeneous integration approach enabled by the inkjet printing technique presented in Chapter 3 was adopted for system integration as presented in Paper III. The $G_{max}/G_0$ of f-MWCNTs sensor was monitored in the demonstration to indicate the ambient humidity level, since it follows the same tendency when the sensor is bent or flat. LEDs were utilized to indicate different RH levels. A novel inkjet-printed electrochromic paper display was studied, and it could be further integrated in this sensor system [91]. The MCU saves the conductance of the humidity sensor.
and compares with the initial value. When the $G_{\text{meas}}/G_0$ varies, the MCU turns the relevant LEDs on. The paper-based sensor card could be bent and folded as shown in Figs.4.11b and c. However, the folding of the sensor and the components should be avoided. As demonstrated, the paper-based smart electronics offers new opportunities for the packaging industry. A more detailed discussion is reported in Paper III.
Chapter 5

Wearable Healthcare Monitoring Devices

The development of flexible and printed electronics offers new possibilities for cost-effective wearable healthcare devices for continuously and unobtrusively monitoring vital biological signals. In this chapter, inkjet printing technique is adopted in the healthcare application. The performance and design rules of printed electrodes are investigated. The heterogeneous integration platform is utilized to integrate the customized silicon System-on-Chip (SoC) with printed electrodes. A prototype of a wearable Bio-Patch was implemented and the performance was evaluated by in-vivo Electrocardiogram (ECG) test.

5.1 Bio-Potential Signals and Customized SoC

Bio-electrical signal sensing and monitoring play an indispensable role for both clinic and healthcare applications [92, 93]. Typical bio-signals include ECG, Electromyogram (EMG), Electroencephalogram (EEG) and Electrooculograms (EOG), with each one corresponding to the relative organs/tissues and indicating the state of health [94]. The features and representative applications of these bio-signals are listed in Table.5.1.

It can be seen that the bio-signals feature small amplitudes and cover the low-frequency range, which poses high demands on the signal detective circuits. In order to achieve high-dynamic range to monitor different bio-signals, a SoC was customized with programmable gain and bandwidth [98]. As shown in Fig.5.1a, three functional blocks are included: an Analog Front-End (AFE), an Analog-to-Digital Converter (ADC), and a digital core. The origin bio-potential is sensed and amplified by the on-chip AFE, digitized by ADC, and then stored, processed or transmitted by the digital core. The Bio-SoC is fabricated with a 0.18 μm standard CMOS technology, and the microphotograph is shown in Fig.5.1b. More detailed information regarding the chip design was presented in Papers IV and
Table 5.1: Features and Applications of Bio-Signals [95, 96, 97].

<table>
<thead>
<tr>
<th>Bio-Signal</th>
<th>Monitor Object</th>
<th>Amplitude</th>
<th>Bandwidth</th>
<th>Application Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>Heart</td>
<td>0.05-5 mV</td>
<td>0.5-200 Hz</td>
<td>Diagnosis of arrhythmia.</td>
</tr>
<tr>
<td>EEG</td>
<td>Brain Activity</td>
<td>1-50 µV</td>
<td>0.5-100 Hz</td>
<td>Sleep studies; Brain-computer interface.</td>
</tr>
<tr>
<td>EMG</td>
<td>Muscle Activity</td>
<td>0.05-20 mV</td>
<td>20-1500 Hz</td>
<td>Assess Muscle function for athletes; Prosthesis.</td>
</tr>
<tr>
<td>EOG</td>
<td>Eye Movements</td>
<td>0.4-1 mV</td>
<td>DC-30 Hz</td>
<td>Eye position track; Sleep state analysis.</td>
</tr>
</tbody>
</table>

In this work, the healthcare monitoring device is designed for the application scenario of ECG monitoring, and therefore the Bio-SoC is configured for ECG signal measurement. Compared with bio-sensing systems made with off-the-shelf components, the SoC solution has four main advantages which are essential for the wearable device [45, 99]:

1. Tiny physical size (3 mm × 1.5 mm), so that it is unobtrusive when integrated with the printed electronics and it also enables the system miniaturization.

2. Low power consumption (20 µW with a 1.2 V power supply), so that long battery life could be delivered.

3. High input impedance (around 40 GΩ at 100 Hz), which eliminates the effect of series resistance induced by printed electrodes, and allows great freedom for electrode pattern design.

4. High Common Mode Rejection Ratio (over 90 dB) and large gain (up to 1660 V/V). Therefore it is possible to obtain high-quality bio-signals with the use of very small and short-distance electrode pairs.

Figure 5.1: the customized Bio-signal System-on-Chip.
5.2 The ECG Signal

Heart disease is one of the major causes of death all over the world [100]. In the case of premature heart attack, the sooner the abnormal heart condition is detected, the lower probability there is that the disease will cause irreparable damage or death. Therefore, long-term real-time monitoring is essential for the elderly or patients with heart diseases [101, 100].

ECG is one of the most commonly used bio-potential signal for detection of heart diseases. According to different application scenarios, the ECG devices/instruments can be divided into two groups: for accurate and professional heart disease diagnosis in the hospital, and for portable daily healthcare especially in home environments. The quantitative requirement of ECG signal varies accordingly. Here we focus on the portable device with single channel ECG monitoring.

The principle and equivalent schematic for ECG measurement is shown in Fig.5.2a. Two electrodes are located at A and B with a certain distance from each other. The electrodes are connected through a pair of interconnects to the Bio-SoC on the testboard. The quality of ECG signal captured is influenced by the location of electrodes, the distance between electrodes, and the contact impedance between the electrode and the skin, which varies according to the electrode topology [93]. An example of the typical ECG waveform is shown in Fig.5.2b consisting of a P wave, a QRS complex, and a T wave.

5.3 Dry Electrodes

The bio-signals propagate from inside the human body to the skin in the form of ionic currents [102]. The electrode transforms the ionic currents flowing in the body into electronic currents, and the characteristics of the electrodes greatly determine
CHAPTER 5. WEARABLE HEALTHCARE MONITORING DEVICES

Figure 5.3: Examples of electrodes based on textiles [106, 107, 108, 109].

the quality of captured biopotential signals [103]. Therefore, the electrode is the key component of biopotential monitoring system [93].

Nowadays, the silver/silver chloride electrode is one of the most commonly used electrodes for clinical/research applications because it is simple, low-cost, and provides good bio-signals [102, 104]. However, problems arise from the electrolytic-gel-based electrodes [105]: 1) signal degradation due to dehydration after long-term use; 2) the material used in the gel may cause irritation; 3) measurement on a hairy chest requires skin preparation which is time-consuming and inconvenient. Therefore, many attempts have been made to overcome the drawbacks. Some novel dry electrodes have been proposed based on different media with varied working principles and suitable application fields.

1. Electrodes based on Textile (TextE).

The fabrication methods include a) conductive yarns weaving, knitting or embroidering along with normal yarns as shown in Fig.5.3a [106] and Fig.5.3b [107], b) screen-printing conductive pastes on top of fabric as shown in Fig.5.3c [108]. The textile-based electrodes could improve the user comfort and be unobtrusively embedded in clothes such as t-shirts Fig.5.3d [109]. Because TextE features lightweight, ductile, washable, and at the same time resisting abrasion and moisture, it is suitable for long-term continuous monitoring [106].

2. Electrodes based on a planar metal plate.

The media could be a standard rigid printed circuit board (PCB) as shown in Fig.5.4a [110], a flexible etched copper plate in Fig.5.4b [111], or on a
5.3. *DRY ELECTRODES*

flexible substrate such as preflex Fig.5.4c and paper Fig.5.4d using printing technology. By attaching the planar metal plate to the skin, an electrical connection could be formed and good performance was obtained in *Paper VI*. Insulated by a dielectric layer, e.g. cloth, this kind of electrodes and the skin form a parallel-plate capacitor and can be used for non-contact bio-signal measurement [111, 110].

3. Spiked electrodes (SpikE).

For special applications, such as ECG measurement on hairy chests, EEG measurements on a hairy scalp, and bio-potential monitoring for animals, the previously mentioned electrodes will encounter certain problems since the hairy skin may lead to an unstable skin-electrode attachment which in turn induces contact noise, and in some cases, results in measurement failure [111]. The solution nowadays is skin pre-treatment to remove some of the hair, but the drawback is uncomfortable and troublesome for the patients. SpikEs are quite helpful for such applications because the metal spikes/needles can easily get through the hair and make contact with the skin to form an electrical connection. Some examples are shown in Fig.5.5 [112, 103]

![Figure 5.4: Examples of electrodes based on planar metal plate [110].](image)

![Figure 5.5: Examples of spiked electrodes [112, 103].](image)
Figure 5.6: Samples of different types of electrodes: a) commercial electrode, b) a pair of inkjet printed electrodes on polyimide substrates, c) the back of textile electrode, d) a pair of spiked electrodes.

In this work, three types of dry electrodes are presented. TextE (Fig.5.6c) is made by woven conductive yarns uniformly in the fabric. SpikE (Fig.5.6d) is made of breadboards and metal pins. In addition, for the first time, inkjet printing technology is being proposed for the manufacture of bio-sensing electrodes (PrintE) on flexible substrates including paper and polyimide (Fig.5.6b). The performance of these dry electrodes is evaluated and compared regarding the aspects of contact impedance and induced noise as presented in Paper VII. In order to further estimate the overall performance of the electrodes, in-vivo tests are applied and the ECG signals captured are shown in Fig.5.7a-d. Commercial pre-gelled electrodes (CommE) shown in Fig.5.6a are used as the reference. The experimental results indicate that TextE and PrintE supply similar ECG signals with CommE, while SpikE induces large noise. However, the QRS complex is visible and the signal quality could be improved by backend signal processing as shown in Fig.5.7e. TextE is comfortable, but it is sensitive to motion and pressure, which requires an efficient way to fasten it to the location. A detailed description regarding the experiments and the results are discussed in Paper VII.

Each type of biopotential electrode has its distinct features. The choice of which one to adopt is left to the user, the patient and the doctor according to the specific application scenario. In the final wearable device demonstration, instead of the other two, PrintE is selected because 1) it performs in a stable way which is comparable with CommE; 2) it is thin, flexible and lightweight; 3) the manufacture process is compatible with the system implementation. In addition, the inkjet printing technique makes it easy to customize the electrode pattern. In order to further understand how the electrode pattern influences the quality of ECG signal obtained, a series of in-vivo tests is applied using printed electrodes with different diameters (3 mm - 15 mm), different distances between the pair of electrodes (2 cm - 14 cm), and different structures (symmetric and unsymmetric). The results indicate that:

1. Within the test range, the amplitude of the ECG signal detected decreases along with the shrinking of electrode size.
5.4 Demonstration: Miniaturized Wearable Bio-Patch

Nowadays, the Holter monitor system (Fig.5.8a) is commonly used for continuous ECG monitoring. However, due to the large size and rigid feature of the device package, this system is not comfortable for long-term daily monitoring. As alternatives, several bio-sensing systems were proposed and implemented by integrating the electrodes with the customized electronic circuits, such as the T-shirt-based wearable ECG monitoring system as shown in Fig.5.8b [100], active electrodes embedded in chairs (Fig.5.8c) [113] and beds (Fig.5.8d) [114]. However, there are still some remaining drawbacks: 1) the systems were made using off-the-shelf components, which leads to a cumbersome sensor size and short battery life; 2) wearable T-Shirts need to be tight enough to ensure good contact between the electrodes and the skin, which is uncomfortable for the elderly for long-term use; 3) a chair/bed based system is suitable for a certain period and not for 24-hour monitoring. Future long-term continuous monitoring devices for healthcare applications require a system which is tiny, wearable, comfortable, low-power and affordable price [115].
CHAPTER 5. WEARABLE HEALTHCARE MONITORING DEVICES

Figure 5.8: Examples of bio-sensing system: a) Holter monitor system, and ECG monitoring device embedded in b) a T-Shirt, c) a chair, and d) a bed [100, 113, 114].

Based on these considerations, a wearable miniaturized Bio-Patch is proposed. Two key components are employed, a mixed-signal Bio-SoC introduced in Section 5.1, and printed electrodes (introduced in Section 5.3). Unlike the integration of packaged chip for intelligent packaging, the miniaturization of a Bio-Patch is critical, which requires the direct integration of a bare die as shown in 5.1. The pad size is 65 $\mu$m with a pitch of 90 $\mu$m. The inkjet-printing-enabled heterogeneous integration platform was used to implement the Bio-Patch. Following the design rules introduced in Chapter 3, the hybrid interconnections are shown in Fig.5.9. The width of inkjet-printed interconnects can be as thin as 50 $\mu$m. In total 14 parallel interconnects are successfully printed within a narrow space of 1.5 mm (one edge of the bare die) without any open-circuits or short-circuits.

The layout of the printed electrodes was optimized considering the trade-off between the quality of the ECG signal and the physical size miniaturization (the diameter of the electrode and the distance between two electrodes). Based on the design rules introduced in the previous section, the electrode pair with the diameter of 9 mm and distance of 4 cm was selected. The Bio-Patch prototype and the ECG signal captured are shown in Fig.5.10. The size of the Bio-Patch is 4.5 cm $\times$ 2.5 cm $\times$ 2 mm. The thickness could be further reduced to 1 mm if a soft battery (e.g.

Figure 5.9: Hybrid integration of Bio-Patch using inkjet printing technology.
Enfucell printed battery) is used. With the help of bio-compatible adhesive tape, the Bio-Patch can be easily attached onto the patient’s chest. Due to the use of thin flexible polyimide substrate and the heterogeneous integration approach for Silicon-on-Flex, the Bio-Patch is small and ultra-thin like a normal ‘Band-Aid’. A more detailed description is presented in Paper II.

Figure 5.10: Miniaturized Bio-Patch for single-channel ECG measurement. Figure adapted from Paper II.
Chapter 6

Summary and Future Outlook

Driven by the concept of the Internet of Things, the market for intelligent devices, which are thin, light-weight, flexible and even stretchable, is exploding. Printing technology is considered to be a revolutionary approach that facilitates the cost-effective manufacturing of such devices. Among other printing techniques, the inkjet printing technique features digital, additive, non-contact, and mask free. These advantages enable the system designer to be free to develop prototypes for functionality verification, while its R2R compatibility makes it easy to adapt the design for high-volume production. However, fully printed transistors are still not comparable with silicon-based ones in terms of performance, density and yield. Fully printed systems cannot fulfill the functional requirements of intelligent device applications in the near future. Therefore, a heterogeneous platform combining silicon and printed electronics is presented and studied. The main contributions of this thesis include the following:

- As the basic component, inkjet printed interconnections on flexible substrates are evaluated. The printing process is optimized for different substrates. The sheet resistance and the reliability against bending, folding and an 85 °C /85% RH ambient environment are used as the evaluation parameters with the application scenario of intelligent packaging and wearable healthcare devices.

- Besides the generally used polyimide and inkjet (photo) paper, ordinary low-cost and high-moisture-resistance package paper is proposed as alternative substrates for paper electronics. The tests prove that package paper is suitable for smart packaging applications that have less strict requirements of conductivity and high demands for moisture resistance.

- The integration approach enabled by conductive adhesives is studied and utilized for the integration of both packaged and bare silicon chips. Based on this approach, two prototypes of wearable bio-patch are presented. However, there are drawbacks which limit the application for silicon-on-paper.
• Due to the non-contact and additive features, the inkjet printing technique is proposed as an integration approach to seamlessly integrate the silicon chip with flexible printed electronics. The integration process is presented and investigated.

• The proposed heterogeneous platform is applied for intelligent packaging by integrating commercially available microcontroller with a customized f-MWCNTs humidity sensor. Bending and folding tests are applied to study the limitation and design guidelines of paper-based electronics. A humidity sensor card is developed to demonstrate the system concept.

• To solve the problems of commonly used electrolytic gel-based electrodes, the textile-based, spiked and printed dry electrodes are presented as alternatives for bio-signal monitoring. Inkjet printing technology enables cost-effective manufacturing of easy-customized electrodes. The performances of dry electrodes are evaluated through ECG \textit{in-vivo} tests. The advantages and disadvantages of each type of electrodes are analyzed and different electrodes are preferable depending on the application scenario.

• The proposed heterogeneous integration platform is adapted for manufacturing wearable healthcare monitoring devices. Three aspects are considered when miniaturizing the device to make it comfortable and unobtrusive: 1) the optimized layout of printed electrodes; 2) the customized low-power and tiny-size bio-sensing chip; 3) the direct integration of the bare die enabled by inkjet printing. The suitability is demonstrated by the prototype of miniaturized Bio-Patch. This heterogeneous integration approach provides a promising solution for future personalized wearable healthcare applications.

Finally, some considerations about future work:

• The paper-based interconnects are not as reliable as polyimide-based ones. In addition, the integration of components reduces flexibility. An efficient and cost-effective way to improve the reliability is needed. One possible solution is adding a thin layer of dielectric material on top of the printed electronics as insulation and protection.

• The two demonstrations presented mainly cover the low-frequency band up to MHz. The integration of a wireless transmission module could provide more attractive functionalities and new applications. The high-frequency characterization of flexible printed electronics is then important and interesting.

• The proposed heterogeneous platform could be adapted for stretchable electronics, which is attractive for wearable devices.
Bibliography


BIBLIOGRAPHY


[18] Flexible applications based on printed electronics technologies.


