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INTEGRATION OF DISTRIBUTED GE ISLANDS ONTO SI WAFERS BY ADHESIVE WAFER BONDING AND LOW-TEMPERATURE GE EXFOLIATION

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ABSTRACT

We present a novel and highly efficient wafer-level batch transfer process for populating silicon (Si) wafers with distributed islands of thin single-crystalline germanium (Ge) layers. This is achieved by transferring Ge from a Si wafer containing thick Ge dies to a Si target wafer by adhesive wafer-bonding and subsequent low-temperature Ge exfoliation.

INTRODUCTION

The combination of electronic, MEMS and photonic functions on a common Si substrate enable high-performance heterogeneous microsystems such as infrared detector arrays, optical gyroscopes or components for optical communication systems [1-7]. However due to the lattice mismatch between Si and typical photonic materials such as Ge, gallium-arsenide (GaAs) or indium phosphide (InP), it is in most cases not possible to directly deposit or grow these type of high-quality photonic materials on top of a Si substrate. An attractive approach to overcome this problem is to transfer a layer of the high-quality photonic material from its original substrate to the Si substrate. This has been implemented mainly by using chip-level processes based on adhesive bonding [8, 9] or direct bonding [10]. In these approaches the photonic material donor substrate typically is sacrificially etched after the bonding step to leave a thin layer of the photonic material on top of the Si substrate. Thereafter the photonic devices on the Si substrate can be defined and formed from the photonic material. However, these processes are very resource demanding since the comparably expensive photonic material substrates are sacrificially removed by grinding and/or etching. Furthermore, due to the difference in coefficient of thermal expansion (CTE) between Si and e.g. Ge or GaAs, it is extremely challenging to utilize large-scale and high-yield wafer-to-wafer bonding at elevated temperatures. An innovative approach to address this problem is to populate the Si wafer with pre-dices dies of the photonic material using pick-and-place positioning of the dies on the wafer along with a subsequent adhesive wafer bonding step. All dies on the Si wafer can then be thinned and processes in parallel fashion using standard wafer-scale processes [3, 6]. Another related process that has been proposed is based on batch-transfer of radially expanded die arrays to achieve efficient layer transfer [11]. However, both these approaches rely on sacrificial removal of the excess photonic donor substrate. In this work we present a wafer-level batch transfer process that is based on transferring Ge from a Si wafer that is containing Ge dies to a Si target wafer by adhesive wafer-bonding and subsequent low-temperature Ge exfoliation from the Ge dies. The bulk of

the Ge dies is remaining on the Si wafer and can in principle be reused to transfer subsequent layers from the remaining bulk Ge dies. Thus, the proposed approach circumvents problems caused by the CTE mismatch between Si and photonic material wafers and avoids the sacrificial removal of the comparably expensive photonic base substrate.

CONCEPT OF THE INTEGRATION PROCESS AND EXPERIMENTS

The conceptual idea for the transfer of thin Ge layers from Ge dies onto a Si wafer consists of starting with a Si wafer containing distributed island of Ge dies. This is used as the Ge donor-wafer which is then adhesively bonded to a receiving Si substrate. Adhesive bonding is attractive for heterogeneous integration processes due to its insensitivity to topographies or particles at the surfaces to be bonded and the resulting high-yield bond interfaces [1]. Since both the target wafer and the donor wafer containing the Ge dies are made of Si, there is no significant CTE mismatch between the two wafers, which avoids problems related to a CTE mismatch during bonding. The hydrogen-implanted Ge dies are exfoliated at a comparably low temperature of 300°C [5], which leaves transferred 1 µm thick Ge layers on the Si target wafer. Figure 1 shows the detailed process scheme that was implemented in this work. In this process, hydrogen is implanted in a Ge wafer surface to a depth of about 1 µm as indicated in Figure 1a. Thereafter a 1 µm thick layer of silicon nitride is deposited on the surface of the Ge wafer using plasma-enhanced chemical vapor deposition as depicted in Figure 1b. Next, the wafer is attached to an expandable UV-release tape and diced into mm-sized dies as shown in Figure 1c. The array with dies is then expanded as depicted in Figure 1d using a matrix expander [4]. A Si wafer is spin-coated with AP3000 adhesion promoter (Dow Chemical Company) at 3000 rpm and spun dry. This is followed by spin-coating a layer of BCB (Cyclotene 3022-46, Dow Chemical Company) that is mesitylene-diluted 1:1 by weight at 5000 rpm onto the Si wafer as shown in Figure 1e. The dilution of the BCB is done to obtain a very thin BCB coating with a thickness of about 550 nm. The spin-coated BCB on the Si wafer is soft-baked at 150°C for 3 min on a hotplate and subsequently slightly crosslink for 5 min at 180°C in an oven. Thereafter, the tape with the expanded Ge die array is pressed onto the BCB-covered wafer and baked for 10 min at 80°C as shown in Figure 1f. The dicing tape is removed by exposing the tape for 10 min to UV-radiation as shown in Figure 1g. A second BCB-coated Si wafer is prepared by spin-coating the wafer with the adhesion promoter AP3000 at 3000 rpm until the

wafer is dry and then spin-coating an undiluted layer of BCB (Cyclotene 3022-46) at 5000 rpm on the Si wafer. This results in a 2.4 μm thick layer of BCB-layer, as depicted in Figure 1h. The BCB-coated Si wafer is then bonded to the Si wafer containing the Ge dies as illustrated in Figure 1i. The wafer bonding is performed in a Suss Microtec SB8 wafer bonder. The combined wafer bonding and Ge exfoliation process consists of 24 h baking at 130°C, followed by a temperature ramp of 1°C

per minute to 300°C. The bonding temperature is kept stable for 10 min followed by cooling the wafer stack to room temperature. The temperature cycling steps crack the thin hydrogen-implanted layer from the surface of the Ge dies at the depth of the hydrogen-implantation [12]. This leaves thin, exfoliated Ge layers bonded with BCB on the target wafer. The bulk Ge dies remain bonded to the Si wafer as illustrated in Figure 1j.

Figure 1: (a) Hydrogen is implanted into a Ge wafer. (b) Deposit 1 μm PECVD silicon nitride onto the Ge wafer. (c) Dice the Ge wafer. (d) Expand the dicing tape to separate the dies. (e) Spin coat BCB onto a Si wafer. (f) Press the expanded die array onto the Si wafer. (g) Remove the dicing tape after the transfer. (h) Spin-coat BCB on a second Si wafer. (i) Press the Si wafer onto the Si wafer containing the Ge dies. Bond the two wafers. (j) Exfoliation of the thin hydrogen-implanted Ge layer by temperature ramping to 300 °C. This process causes the cracking of a thin layer of Ge from the surface of the Ge dies. Thus, 800 nm thick exfoliated Ge layers are left on the Si target wafer. The bulk Ge dies remain bonded on the Si handle wafer.

RESULTS

Figure 2 depicts experimental results from studying the fabrication process as described in Figure 1. Figure 2a shows a 15 mm square Ge die that is attached to an expandable dicing tape. Figure 2b shows the same Ge die after dicing and tape expansion to separate the Ge dies before their transfer to a Si wafer using adhesive bonding.

Figure 2c shows four arrays of Ge dies bonded to a Si wafer as depicted in Figure 1g. The dies are squares and have sizes of 2 mm, 2.5 mm, 3 mm and 5 mm respectively. Figures 3 and 4 illustrate the results following the wafer bonding and Ge exfoliation steps as depicted in Figure 1i and 1j. Figure 3a and 3b are images of Si wafers with bonded and exfoliated Ge dies.

Figure 3a shows a Si handle wafer with adhesively bonded bulk Ge dies after the Ge exfoliation step. Figure 3b shows the respective Si target wafer containing the transferred 1 μm thick Ge layer islands. Figure 4a shows the results from an EDX material analysis to confirm that Ge has been transferred. Figure 4b shows one bulk Ge die on the donor wafer after exfoliation. Figure 4c shows a transferred and exfoliated Ge layer island on the target Si wafer.

Figure 2: (a) Square 15 mm Ge die attached to an expandable UV-release dicing tape. Results following the step shown in Figure 1c. (b) Expanded die array. Results following the step shown in Figure 1d. (c) Four arrays of dies transferred and BCB-bonded to a 100 mm diameter Si wafer. Results following step shown in Figure 1g.

Figure 3: (a) Bulk Ge dies BCB bonded to a 100 mm diameter Si wafer. Results following step shown in Figure 1j. (b) Thin exfoliated Ge layer islands that are BCB bonded to a 100 mm diameter Si wafer. Results following step shown in Figure 1j.

Figure 4: (a) EDX scan confirming that Ge was transferred. The color coding corresponds to concentration of Ge and Si. (b) SEM image of a bulk Ge die on the Si donor wafer after exfoliation. (c) Transferred and exfoliated Ge thin layer island that is bonded to the Si target wafer.

The results from the experiments depicted in Figures 2, 3 and 4 conclusively demonstrate that it is possible to use adhesive bonding and subsequent exfoliation of thin Ge layers to transfer Ge from a donor wafer and populate a Si target wafer with thin-film Ge islands in a controlled way. This approach could be a step towards cost-competitive and resource efficient heterogeneous integration of active photonic materials in Si-based platforms. Potential applications could be advanced heterogeneous Si photonics for optical communication systems and high-performance infrared bolometer arrays.

CONCLUSIONS

In summary, we have demonstrated the viability of a new process scheme for resource efficient and wafer-level transfer of high-quality photonic materials, in this case Ge, on top of a silicon wafer. The proposed heterogeneous integration process is based on adhesive wafer bonding with BCB as the intermediate bonding layer and subsequent exfoliation of a thin layer from the photonic material donor substrate. The process can be implemented on wafer-level and is potentially more resource efficient than conventional schemes using chip-to-wafer bonding together with sacrificial substrate removal.

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