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Fabrication of an Infrared Emitter using a Generic Integration Platform Based on Wire Bonding

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Abstract. This paper reports a novel approach for the fabrication of infrared (IR) emitters for non-dispersive infrared gas sensing. The proposed concept enables the integration of superior resistive heater materials with microelectromechanical systems (MEMS) structures. In this study, non-bondable filaments made of nickel chromium are attached to mechanical attachment structures using a fully automated state-of-the-art wire bonder. The formation of the electrical contacts between the integrated filaments and the electrical contact pattern on the substrate is performed using conventional gold stud bumping technology. The placement accuracy of the integrated filaments is evaluated using white-light interferometry, while the contact formation using stud bumping to embed the filaments is investigated using focus ion beam milled cross-sections. A proof-of-concept IR emitter has been successfully operated and heated up to 960 °C in continuous mode for 3 hours.

Wire bonding, integration platform, stud bumping, MEMS, MEMS-based infrared emitter, NDIR, gas sensing, non-bondable materials, nickel-chromium wire, NiCr filament, Nikrothal wire, resistive heating, joule heating:

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1. Introduction

Smart gas sensing systems have been successfully introduced to a variety of commercial and industrial applications. Gas sensing systems are for example used in the health care sector for breath diagnostics [1, 2], to monitor specific gaseous substances in the agricultural and processing industry [3, 4, 5], to control carbon dioxide concentrations in heating ventilation and air conditioning (HVAC) systems [6, 7, 8, 9, 10] and to investigate environmental changes of the climate [11, 12, 13]. Especially gas sensing systems based on non-dispersive infrared (NDIR) spectroscopy have attracted very large interest due to the simplicity of the sensing principle and for being cost-efficient in fabrication [14]. These sensor systems offer high selectivity among traceable gases as well as a considerable sensitivity to gas concentrations in the low ppm range [15, 16, 17]. State-of-the-art NDIR systems are compact, fast, reliable and enable real-time analysis. A conventional NDIR sensor system makes use of wavelength selective absorption characteristics in the infrared region of the targeted gas, where the gas molecules exhibit specific vibrational or rotational excitation modes. The absorption results in a reduction of signal intensity at the detector side of the NDIR system and enables an efficient qualitative and quantitative detection of gaseous molecules, such as carbon monoxide, carbon dioxide, methane, ethane as well as ammonia.

The characteristics of the infrared emitter source have a significant impact on the performance of the NDIR sensor system, the spectroscopic coverage and the total costs of the system. Traditionally incandescent micro light bulbs have been widely utilized as broadband infrared emitter in NDIR systems. Typically, these emitter sources consist of a double-coiled filament made of tungsten that is manufactured using a laborious semi-automated fabrication process [3]. Incandescent micro light bulbs offer a high spectral emission [18], but the IR transmission through the glass envelope drops significantly for wavelengths larger than $4.5\mu\text{m}$. Therefore, their application for gas detection systems using the mid and far infrared wavelength range is not ideal. Hence there is a need for alternative IR emitters to overcome the limitations of the traditional emitter source.

IR emitters based on microelectromechanical systems (MEMS) technology are regarded as a promising approach, enabling low to moderate modulation frequencies, emitting a gray body radiation spectrum beyond $4.5\mu\text{m}$ and offer low power consumption. Typically, MEMS IR emitters utilize silicon as substrate material and the active emitting structure is either formed on top of a membrane [19, 20, 21], on a suspended micro hotplate [22, 23, 24] or on other suspended micro bridge structures [25, 26]. To improve the emissivity of emitter surfaces, the deposition of carbon-based films [27, 28] as well as the modification of the bulk or surface texture of the emitting component has been proposed [29, 30, 31]. Platinum is frequently proposed for the fabrication of IR emitter sources due to its high melting point and oxidation resistance [19, 26, 24]. However, platinum has a 16 times higher coefficient of thermal expansion (CTE) compared to silicon dioxide (SiO_2), is known to have a low emissivity in the near to mid infrared region [32], and generates high thermally induced mechanical stresses

during device operation. Therefore, platinum is not the ideal emitter material for highly efficient and reliable MEMS-based IR emitters. Various fabrication approaches for realizing IR emitters have been reported that are based on silicon-on-insulator (SOI) substrates [23, 33, 27, 34, 31]. While the use of SOI substrates allow elegant and simple fabrication solutions to realize membrane or micro hotplate-type MEMS emitters, the high costs of SOI substrates does not meet the cost targets for replacing the low-cost incandescent light bulbs in NDIR gas sensing systems. Thus, to satisfy the performance and cost requirements of NDIR systems, alternative fabrication approaches are needed for realizing IR emitter sources.

This paper focuses on the fabrication of a joule-heated IR emitter for NDIR sensing systems, using a state-of-the-art automatic wire bonding tool, for placing and attaching nickel-chromium filaments as IR emitter source. The material composition of the nickel-chromium wire does not allow conventional wire bonding, due to the absence of forming a diffusion bond or and intermetallic compound. Therefore, the filament integration process requires special silicon attachment structures. The proposed approach makes use of a previously reported process for non-bondable wire materials and has been further developed to a mature integration platform utilizing a fully automated state-of-the-art wire bonding tool [35]. Wire bonding has been the dominating die to package interconnection technology for several decades and commercial wire bonding tools offer a high throughput at comparable low-costs [36]. Recently presented micro-fabrication and packaging concepts using wire bonding have revealed wire bonding as an attractive and multipurpose fabrication technology [37, 38, 39, 40, 41, 42, 43, 44].

2. IR Emitter Design and Integration Process

2.1. IR Emitter Design

Figure 1 shows a schematic of the grid emitter, which is made of three functional areas, whereupon the centered emitting area, highlighted in red, is placed between the hook-in and the squeeze-in attachment areas, both highlighted in blue. The grid emitter consists of a rectangular silicon frame, where 20 parallel filaments are suspended over a cavity in the emitting area. Thus, the area of physical contact between the integrated filaments and the silicon substrate is reduced and heat conduction from the emitting area to the substrate is minimized. Both the hook-in and the squeeze-in area facilitate a structural rigid attachment of the filaments and the formation of electrical contacts. The hook-in area contains two rows with 10 hook-in structures each, that allows the attachment of the free air ball (FAB) to the substrate. Each hook-in structure has the shape of a vertical trench opening on top of a buried cavity, as illustrated in figure 1. The FAB is placed into the buried cavity, which is laterally accessible by an adjacent, rectangular opening through the substrate. The squeeze-in area on the opposite side of the emitting area contains one row of 20 squeeze-in structures allowing the clamping of the ends of the filaments and enable the cut-off of the filament wires. Each squeeze-in attachment

structure has the shape of a tapered vertical trench through the substrate, where the filament is squeezed into the trench. For the infrared emitter, we have used resistive heating wires, type Nikrothal, supplied by Sandvik AB, Sweden [45]. Nikrothal refers to an commercially available family of austenitic nickel-chromium alloys (NiCr alloy) that are per se non-bondable, as no diffusion or intermetallic compound bond is formed when conventional micro welding is attempted. Nikrothal wires offer a maximum operation temperature of 1200 °C, high resistivity and excellent oxidation resistance. Oxidized Nikrothal wires features a high coefficient of emissivity of 0.88. This makes Nikrothal resistive wires a very suitable material for high-temperature applications, such as IR emitters.

Figure 1: Three-dimensional model of the infrared emitter design (to scale). The grid emitter consist of two attachment areas, highlighted in blue, to mechanically fixate the 20 parallel integrated Nikrothal wires over the rectangular substrate frame that forms the emitting area, highlighted in red. The close-ups to the lower left and to the upper right illustrate details of the hook-in structure and squeeze-in structure, respectively.

Figure 2: Conceptual scheme of the wire integration process. A 3D cross-section of the grid emitter substrate is depicted in the upper part of the drawing. Details of the individual integration steps are illustrated in each of the close-up illustrations. The hook-in sequence visualizes the guiding of the FAB underneath the wire capillary into the buried cavity of the hook-in structure (I) - (III). The wire capillary moves upwards out of the vertical trench towards the squeeze-in structure and the filament is guided over the emitting area (III) - (IV). As the wire capillary approaches the squeeze-in structure, the filament is forced into the trench (V) and cuts-off the filament wire at the bottom of the squeeze-in structure (VI).

2.2. Filament Integration Process

The Nikrothal wire integration is achieved by utilizing the functional attachment structures located on the emitter substrate. The integration cycle of the filaments have been carefully adapted to conventional ball bonding technology. This potentially allows the migration of the integration platform to a variety of ball wire bonding tools, as long as the tool allows to modify the trajectory of the wire capillary. Figure 2 depicts the conceptual integration sequence for one filament. The individual integration steps are illustrated in the close-ups of figure 2 to visualize the hook-in sequence (I) - (III) and the squeeze-in as well as the final cut-off of the filament wire (V) - (VI). The integration of the emitter filament begins with the formation of the FAB. A pre-defined tail length of Nikrothal wire below the wire capillary is melted by an electrical discharge, also referred to as electronic flame-off (EFO). The melted alloy forms a sphere and solidifies. Formation of the FAB in argon atmosphere is essential, as any oxidation of the melted alloy causes a non-spherical shape and weakens the mechanical integrity of the FAB. The wire tensioner of the wire bonder pulls the excessive tail into the

wire capillary to center the FAB underneath the capillary (fig. 2, I). Next, the FAB is guided into the hook-in structure of the substrate. Therefore, the wire capillary moves downwards in the rectangular opening adjacent to the vertical trench and performs a touchdown on the substrate carrier (fig. 2, I - II). The FAB is not deformed by this step as no significant bond force is applied. The touchdown defines the origin of the wire integration trajectory. The wire capillary moves upwards until it reaches a height that allows laterally accessing the vertical trench. Next, a lateral movement of the wire capillary to the end of the vertical trench places the FAB into the buried cavity underneath the vertical trench (fig. 2, II - III). The FAB remains in the hook-in structure, while the wire capillary moves upwards out of the vertical trench (fig. 2, IV). Subsequently, the wire capillary moves towards the second attachment structure, while guiding the filament across the rectangular silicon frame to the squeeze-in structure on the opposite side of the emitting area. A final stitch bond sequence is performed to stretch the filament, then to attach the filament and finally to cut-off the wire by applying a mechanical force with the capillary to the wire (fig. 2, V - VI).

For the filament integration process a custom-designed wire capillary was used. Various critical aspects have been incorporated in the capillary design to meet the requirements of the integration approach using a fully automated wire bonding tool. The attachment of the FAB into the hook-in structure requires the formation of a FAB that exceeds the tip diameter (T) of the wire capillary. The lateral trench width (here: $95\text{ }\mu\text{m}$) and the lateral acting shear forces during the integration process define the geometrical parameters of the capillary. Figure 3 depicts the cross-section of the wire capillary tip. The wire capillary has a straight tip with a bottle neck height (BNH) of $90\text{ }\mu\text{m}$ and a bottle neck angle (BNA) of 0° . A tip diameter of $85\text{ }\mu\text{m}$ and a hole opening (H) of $33\text{ }\mu\text{m}$ defines the wall thickness ($26\text{ }\mu\text{m}$) of the wire capillary. Another critical aspect is friction of the wire at the edge of the capillary hole when the wire is guided over the substrate. The exit hole rounded (EHR) refers to the edge radius inside chamfer of the bottle neck end, which is needed to avoid damage of the wire surface.

Figure 3: Cross-section of the tip of the wire capillary with critical features.

Figure 4: Illustration of the electrical contact formation. A gold stud bumps is bonded onto the filament forming an electrical contact between the filament and the contact pad on the substrate.

2.3. Electrical Contact formation

After the integration of the filaments, electrical contacts between the filament wires and the gold pads on the substrate have to be established. While the IR emitter is heated, the Nikrothal filaments oxidize and form a stable insulating outer layer. First, any oxidation of the filament at the contact interface between the filament and the metal pad on the substrate would result in electrically disconnected filament wires. Second, a heated filament that is mechanically attached on both ends to the substrate, experiences thermal expansion that can cause bending of the filament wire away from the contact pads on the substrate. If a filament disconnects or detaches in this way from the contact pads a failure of the IR emitter will be the result. For these reasons, the formation of mechanically and electrically stable contacts between the filaments and the contact pads on the substrate are essential. To address these contact challenges, conventional gold stud bumping is proposed, as illustrated in figure 4. Gold is a well-established contact material in wire bonding for packaging applications, as it allows stable and reliable contact formation. In our applications, gold stud bumping allows encapsulation of the filaments, electrical contact formation, and strong mechanical attachment of the integrated filaments to the contact pads on the substrate.

In this process, the bond capillary with the gold FAB is centered over the metal contact pad with the filament wire on top. The bond capillary moves down and performs a standard gold ball bond. The filament is thereby enclosed by the stud bump and a mechanically stable, electrical contact between the filament, the stud bumps and the bond pad is achieved.

3. Fabrication

The IR emitter is manufactured in three sequential fabrication processes. First the substrate structures are fabricated using conventional MEMS manufacturing. Second a fully automated wire bonding tool is utilized to integrate the filaments forming the emitting area. Finally mechanical on-pad fixation and electrical contacts are established using gold stud bumping technology.

Figure 5: Schematic of the substrate fabrication process. (a) Patterning of the silicon dioxide mask on the back side of the DSP silicon wafer and formation of the buried cavity using anisotropic dry silicon etching. (b) Patterning of the substrate top side using lithography and dry silicon dioxide etching. (c) Anisotropic dry etching of silicon to form the attachment structures. (d) Removal of the silicon dioxide mask, re-oxidation and formation of metal pads.

3.1. Substrate fabrication

The substrate is fabricated using a 100 mm double side polished (DSP) silicon wafer with a thickness of 300 μm. The wafer is thermally wet oxidized and patterned on the back side using lithography. Dry etching of the 1 μm thick silicon dioxide opens the back side of the buried cavities of the hook-in structures and forms a silicon dioxide mask. A 240 μm deep anisotropic silicon etch using the Bosch process forms the buried cavities (fig. 5a). Next, the rectangular opening and the trench of the hook-in structures as well as the entire squeeze-in structures are patterned on the top side of the wafer using lithography. Silicon dioxide etching transfers the resist pattern to the silicon dioxide mask (fig. 5b). A second anisotropic silicon etch on the top side finalizes the formation of the recesses of the hook-in structures, the openings of the emitting area and squeeze-in structures, simultaneously (fig. 5c). Removal of the silicon dioxide mask in hydrofluoric acid (HF) and thermal re-oxidation is required to electrically isolate the attachment structures. To pattern the metal contacts on the silicon substrate, spray-coating of the photo resist is used for conformal coating of the 3D structures. Electron beam evaporation is used to deposit 20 nm titanium and 300 nm of gold. A final lift-off process forms the metal pads for fixation and electrical contact of the filaments (fig. 5d).

3.2. Filament integration

Wire integration is performed using a commercially available state-of-the-art industrial wire bonding tool (ESEC 3100 plus, Besi Switzerland AG, Switzerland).

Table 1: Free air ball formation parameters in argon atmosphere.

Free air ball formation parameter	Value
Electrode to wire distance	1000 μm
Pre-spark voltage	4500 V
Electronic flame-off current	100 mA
Electronic flame-off time	5 ms
Tail length	1000 μm
Free air ball diameter	110 μm

The wafer is temporarily bonded on a carrier plate using adhesives. Next the carrier plate is placed and fixated by vacuum on the heater plate of the wire bonder. The wire integration is performed at 40 °C according to the procedure described in section 2.2. A FAB with a diameter of 110 μm is generated, consuming a length of 700 μm Nikrothal wire. This generates a sufficiently large overlap between the width of the vertical trench of the hook-in structure and the diameter of the FAB. Table 1 lists the parameter for the FAB formation. The touchdown of the FAB on the carrier plate is performed using a minimum impact and bond force of 100 mN and 50 mN, respectively. The bond time is reduced to 10 ms. The touchdown defines the beginning of the trajectory and the capillary moves along the wire integration trajectory to attach the ball and place the filament using a total looping time of 450 ms. The final stitch bond consists of two impact and six bond sequences. The first impact sequence utilizes a force of 50 mN to execute the touchdown of the filament on top of the tapered vertical trench of the squeeze-in structure. The second impact sequence initiates the tensioning of the filament by laterally dragging the wire capillary along the squeeze-in structure. The first and the following four bond sequences continue the tensioning of the filament wire while the integration capillary moves towards the end of the rectangular opening of the squeeze-in structure. Simultaneously, the bond force increases and the filament is forced down into the vertical trench. The fifth and sixth bond sequences finalize the attachment and cuts-off the wire at the bottom of the opening. Table 2 lists the impact and bond sequences of the stitch bond to perform the final attachment and cut-off of the filament. Figure 6 depicts the final device after filament integration. The close-up in the lower left corner reveals a FAB in the hook-in structure. Details of the ends of the filament wires at the squeeze-in structure are shown in the upper right close-up. The filaments are pressed into the tapered trench, resulting in press-fit attachments.

Table 2: Stitch bond parameters for performing the filament attachment into the squeeze-in structure.

Squeeze-in sequence	Force [mN]	Time [ms]	Scrub [μm]
Impact 1	50	100	0
Impact 2	50	100	50
Bond 1	100	100	50
Bond 2	100	100	50
Bond 3	100	100	50
Bond 4	200	100	0
Bond 5	800	100	25
Bond 6	1000	100	25

Figure 6: SEM image of a fabricated IR emitter. The lower left close-up shows a FAB, that is inserted into the hook-in structure of the silicon substrate. The upper right close-up depicts filaments attached into the squeeze-in structures.

3.3. Formation of the electrical contacts

Electrical contacts are established between the Nikrothal filaments and the electrical contact pads on the substrate using conventional gold stud bumping technology. Figure 7 (left) depicts the contact formation between the integrated filament wire and the metal pad on the substrate at the hook-in structure using a stud bump. The gold stud bump is heavily deformed and enclosed the filament underneath. The contact formation at the squeeze-in structure, shown in figure 7 (right), with the filament embedded in the stud bump and pressed into the tapered trench to enhance the mechanical attachment. Using a FAB with a diameter of $75\mu\text{m}$ in combination with an impact of 650 mN and a bond force of 750 mN results in a stable attachment and electrical contact of the filament at the hook-in structure. The metal contact formation at the squeeze-in structure was

Figure 7: SEM images of the electrical contacts between the integrated filaments and the metal pad using conventional stud bumping technology. A gold stud bump that embeds the filament at the hook-in structure (left) and a filament that has been forced into the tapered trench of the squeeze-in structure (right) is shown.

done using a FAB with a diameter of $60\text{ }\mu\text{m}$ and an impact and bond force of 650 mN and 550 mN , respectively.

4. Characterization

To characterize the fabricated grid emitter, the integrity of the mechanical filament attachment is evaluated using conventional pull testing, the placement accuracy of the filaments is characterized and a cross-sectional analysis of the stud bump structures is conducted. Finally, a basic functional characterization of the IR emitter is performed.

4.1. Characterization of the mechanical attachment

The mechanical attachment strength of the filaments to the substrate is characterized by bond wire pull tests [36]. Destructive bond pull tests result in a detached or torn-off filament, which provides information on the failure mechanism. A conventional pull tester (Nordson Dage 4000, Nordson Corporation, US) is utilized to perform the pull tests. The hook of the tool is placed centered underneath the integrated filament and lifted vertically upwards until the mechanical load on the filament results in failure of the filament attachment. Pull tests were conducted according to the MIL-STD-883 standard using two test substrates, each containing 20 integrated filaments with a length of 3 mm , with and without stud bumps to confirm if an additional mechanical fixation by stud bumps improves the attachment strength between the filaments and the substrate [46]. Pull tests of the integrated filaments without stud bumps showed a mean pull strength of 172.04 mN with a standard deviation of 35.01 mN . The mean pull strength of the integrated filaments with stud bumps amounts to 221.02 mN with a standard deviation of 44.09 mN . Several failure modes have been identified. The majority of the integrated filaments with and without a stud bump fixation are torn off at the free air

Figure 8: Graphs of the maximum, minimum and averaged filament placement accuracy averaged over 22 integrated filaments.

ball - wire interface. This indicates that a mechanically fragile heated affected zone (HAZ) is originated, while the formation of the free air ball. Pull tests on integrated filaments with stud bump attachment showed two additional failure mechanisms. The first failure mode is that the filament is disrupted at the hook of the wire pull tester. The second failure mode is that the filament is loosened and free to move while the stud bumps are still attached to the substrate. The MIL-STD-883, Method 2011.9 to evaluate the bond strength of bond wires, defines the minimum bond strength of a pre-sealed bond wire with a diameter of $25.4\mu\text{m}$ to 24.52mN for aluminum bond wires and to 29.42mN for gold wires, respectively. The additional attachment of the filaments using stud bumps has improved filament fixation and results in pull forces up to 9 times higher than the minimum required pull force for aluminum bond wires. As all filaments consistently withstand pull forces near and above 100mN , indicating a sufficient mechanical attachment of the filaments to the substrate.

4.2. Characterization of the filament placement

A reliable placement of the filaments is crucial for the functionality of the emitter and has therefore been evaluated. Inaccurate placement of the filaments may create hot-spots, affecting the temperature distribution over the emitting area and potentially result in a reduced lifetime or malfunction of the device. The placement accuracy of the filaments has been studied on a test device that contains 22 integrated filaments using an optical profilometer (Wyko NT9300, Veeco, US). Figure 8 depicts the out-of-plane placement of 22 filaments. The average out of the substrate plane filament extension is highlighted in green, while the maximum and minimum out of the substrate plane wire extension are highlighted red and blue, respectively. The standard deviation of the filament position is plotted in pink. All filaments are measured across the entire emitting area with a length of 2.5mm . The reference plane is equal to the diameter of the filament, and thus the minimum height of the filament placement is the diameter of $25\mu\text{m}$ of the integrated

Figure 9: SEM images of the FIB milled cross-sections for investigating the embedding of the filaments at the hook-in structure (left) and studying the filament deformation at the squeeze-in structure (right). The left SEM image shows the contact interface between the filament on top of the metal pad and the gold stud bump. The right SEM image shows a cross-section of the filament that has been mechanically forced into the vertical trench. The oval outer contour of the filament cross-section in the trench is highlighted.

filaments. The out-of-plane filament placement shows several maxima and minima at the beginning and at the end of the emitting area. The averaged filament placement accuracy shows consistent placement height between $27\text{ }\mu\text{m}$ to $30\text{ }\mu\text{m}$, while the standard deviation is between $1\text{ }\mu\text{m}$ to $2\text{ }\mu\text{m}$ over the entire emitting zone. These measurements confirm a stable and reliable filament integration procedure.

4.3. Cross-sectional analysis of the electrical contacts

Contact formation of the filaments with stud bumps at the metal pads of the hook-in and squeeze-in structure is investigated using cross-sections. Preparation of the cross-sections was performed using focus ion beam (FIB) milling. Figure 9 (left) illustrates the cross-section of the contact formation at the hook-in structure. A third of the gold bump is entirely milled away, while the filament is partially removed to expose the contact interface to the gold bump. The cross-section displays a complete embedding of the filament by the gold bump on top of the contact pad. Figure 9 (right) shows a cross-section at the squeeze-in structure. The deformation of the filament from an initial circularly shaped wire with a diameter of $25\text{ }\mu\text{m}$ to an oval shaped wire cross-section with a width of $21\text{ }\mu\text{m}$, confirms the mechanical press-fit attachment of the filament into the vertical, tapered trench of the silicon substrate. Only the outer periphery of the mechanically deformed gold stud bump is observable that encapsulates the filament and establishes a stable electrical contact. The cross-sections confirm that conventional gold stud bumping is a suitable solution to embed integrated filaments and establish an

Figure 10: Photograph of the emitter device during the burn-in of the filaments after dicing and packaging in a TO-39 package. A current of about 200 mA is applied and the filaments are heated for 2 min until a stable oxidation layer is formed and the device emits in the visible wavelength range.

electrical contact between the filament and the metal pad.

4.4. Basic functional characterization of the IR emitter.

Basic electrical characterization of the fabricated IR emitter has been performed to confirm the functionality of the emitter. Figure 10 shows a photograph of the device after dicing and packaging in a TO-39 package, during the burn-in procedure. The emitter has been operated for 3 hours in a continuous DC mode, without a malfunction. As conventional NDIR systems are operated in puls mode, the continuous mode can be considered as a stress test to exclude premature malfunction of the emitter device. A 3 hour continuous DC mode corresponds to 60 h operation in pulse mode with a duty cycle of 5 %. In continuous mode, a maximum temperature of about 960 °C has been reached and the power consumption is about 610 mW. Figure 11 shows the I-V curves of three emitter devices. Emitter device 1 and 2 have a ohmic resistance of about 38 Ω and 41 Ω , respectively. In this configuration, each of the ten filaments are connected in series and then wired in parallel. Emitter device 3 connects 20 filaments in series and has a resistance of about 140 Ω . All three I-V curves confirms that the contact formation using stud bumping is a suitable technology to establish reliable mechanical and electrical contacts between the filaments and the substrate.

5. Discussion and Conclusion

We have successfully demonstrated a novel manufacturing technique for MEMS-based IR emitters that are based on heating of metal filaments. In this proof of concept demonstration, deep reactive ion etched silicon has been utilized as emitter substrate. However it is possible to potentially substitute the silicon with a more cost-efficient substrate material, such as low-temperature co-fired ceramic (LTCC). In the experimental demonstration of the IR emitter fabrication, the formation of the FAB on

Figure 11: Basic I-V curve of three different fabricated emitters.

the metal wire has been generated while the EFO electrode and the filament tail has been flushed manually with argon and the wire tail prior to the next integration cycle has been formed manually. We have demonstrated that the filaments can be very precisely placed and integrated using the wire bonding tool. The proposed contact formation between the filament and the contact pads on the substrate using stud bumping has been investigated using cross-sections, confirming that our technology can effectively encapsulate the filament and form excellent mechanical and electrical contacts between the filaments and the contact pads on the substrate. Fabricated emitter devices have been successfully operated and device degradation has not been observed during 3 h of operation.

In summary, the presented approach enables the efficient integration of high-performance NiCr alloy filaments for resistive heating applications into MEMS substrates. The focus of the paper has been to proof the feasibility of our proposed integration platform, utilizing a fully automated state-of-the-art wire bonding tool to perform the entire back-end processing. Furthermore we have demonstrated the basic functionality of the IR emitter, including burn-in properties, I-V characteristics, initial reliability data, and operating temperatures. Our integration platform is a generic, effective and fast fabrication approach that is not exclusively limited to implement resistive heating filaments for high-temperature IR emitter applications.

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