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Optical Characteristics of GaAs MSM Photodetectors Flip-Chip Bonded Upon Micromirrors Using Micromachined Conductive Polymer Bumps

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ABSTRACT

Using flip-chip bonding techniques with micromachined conductive polymer bumps and passive alignment techniques with electroplated side alignment pedestal bumps, a prototype MOEMS structure for optical I/O couplers has been designed, fabricated and characterized. A top MOEMS substrate has through holes, contact metal pads, and side alignment pedestals with electroplated copper to align GaAs MSMs. Conductive polymer bumps have been micromachined on contact metal pads of GaAs MSMs using thick photoresist bump-holes as molding patterns. A diced GaAs photodetectors die with micromachined conductive polymer bumps was aligned to the side alignment pedestals within ± 5 μm and flip-chip bonded onto the substrate. This conductive polymer flip-chip bonding technique allowed a very low contact resistance (~10 mΩ), a lower bonding temperature (~170 °C), and simple processing steps. The GaAs MSM photodetectors flip-chip mounted on the top of OE-MCM substrate showed a low dark current of about 10 nA and a high responsivity of 0.66 A/W. By using bulk-micromachining, conductive polymer flip-chip bonding, and passive pedestal alignment techniques, a prototype MOEMS structure for optical I/O couplers realized in this work shows high potential to use as a fundamental building block in OE-MCMs.

Keywords: flip-chip bonding, conductive polymer bumps, MOEMS, optical I/O couplers, optical interconnections, GaAs MSM photodetectors, passive alignment, low temperature bonding

1. INTRODUCTION

The integration of optical interconnection networks with electrical multichip modules, known as optoelectronic multichip modules (OE-MCMs), is attractive for many communication systems because of the high performance interconnections within microelectronic systems [1]-[7]. For the realization of cost-effective and compact OE-MCMs, a modular arrangement using a hybrid integration of optoelectronic interconnection, multichip modules (MCMs) packaging, and micro-electro-mechanical systems (MEMS) technologies can be a practical solution. This structure implies micro-opto-electro-mechanical systems (MOEMS) at the module level. In the building of OE-MCMs, optical input/output (I/O) coupler is one of the core components. Fig. 1 is a schematic diagram of a micromachined optical I/O coupler, which is composed of three components: photodetectors; integrated electrical MCMs, and micromachined micromirrors and V-grooves. These three components are independently fabricated, and then assembled to construct the optical I/O coupler using flip-chip bonding techniques [6]. The use of flip-chip bonding techniques has grown in many packaging schemes due to the advantages of improved reliability, lower costs, and higher I/O density in less packaging space [5]-[16].

In developing flip-chip bonding techniques for MOEMS devices and systems, OE-MCMs or optical interconnections, most important issues are flip-chip bonding alignment and bonding temperature. The precision flip-chip bonding alignment

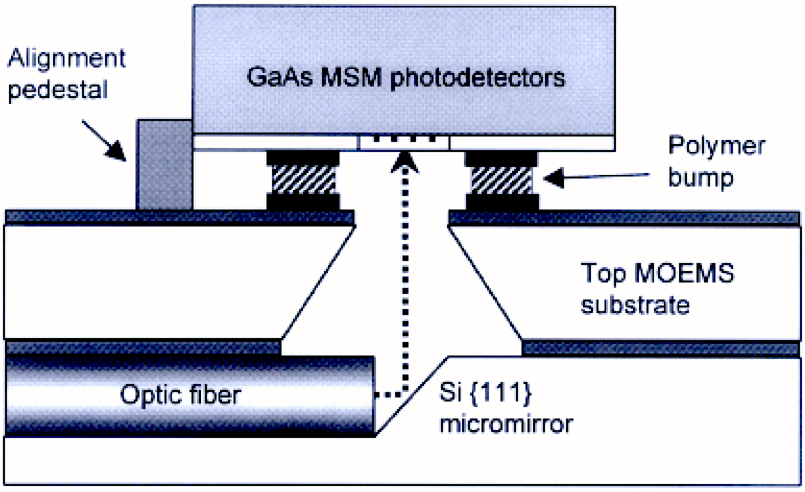


Fig. 1. Schematic diagram of a prototype MOEMS structure for optical I/O couplers which is composed of a flip-chip photonic device and a MOEMS substrate.

techniques of optoelectronic devices are especially important for direct optical input/output coupling with waveguides or optic fibers [8]-[15]. Also, there has been a large demand for the development of flip-chip bonding techniques that have an excellent bumping alignment resolution, keeping its low temperature bonding process [16]-[18]. In this paper, we describe in detail a new approach to address the problems which can be caused by solder bonding techniques and screen printing based polymer bonding techniques, such as high bonding temperature and poor bumping alignment. Using flip-chip bonding techniques with micromachined conductive polymer bumps and passive alignment techniques with electroplated side alignment pedestal bumps, a prototype MOEMS structure for optical I/O couplers has been designed, fabricated and characterized.

2. DESIGN AND FABRICATION

The prototype MOEMS structure for optical I/O couplers is composed of a flip-chip photonic device and a MOEMS substrate, shown in Fig. 1. The flip-chip device is GaAs metal-semiconductor-metal (MSM) photodetectors with micromachined conductive polymer bumps. The top MOEMS substrate includes contact metal pads, electrical metal lines, side alignment pedestal bumps, and through holes. In order to complete optical I/O couplers, {111}-oriented silicon micromirrors and V-grooves will be micromachined on a bottom silicon substrate. In this paper, only the photodetectors and the top MOEMS substrate were designed and fabricated.

2.1 GaAs Metal-semiconductor-metal Photodetectors

GaAs MSM photodetectors, which consist of two, back-to-back Schottky diodes, were formed by depositing two interdigitated metal electrodes on a lightly doped GaAs substrate as shown in Fig 2. A series of photodetectors were designed with finger linewidths of 1, 2 and 3 μm, a fixed finger spacing of 3 μm, and a fixed detector area of 100 μm x 100 μm, in order to permit the ease of alignment with the optical beam reflected from the silicon micromirror. The finger spacing of 3 μm was chosen to give a better responsivity while maintaining an adequate high frequency performance. The mask set and fabrication process was designed to consist of four mask levels. The schematic fabrication process of the photodetectors is summarized in Fig. 3(a). The first mask contained the electrode patterns for Schottky metal fingers using thin Ti/Pt/Au (30/20/100 nm) metal. A lift off process with a chlorobenzene treatment was used to form the narrow metal fingers. As a passivation and anti-reflection layer, a polyimide film was spin-coated and then the second mask was used to define the windows for etching through the polyimide of via holes by reactive ion etching (RIE). The third mask was designed to define larger (500 μm x 500 μm) Ti/Au (50/300 nm) contact metal pads. A fourth mask was used to define molding patterns for thermoplastic conductive polymer bumps (400 μm x 400 μm).

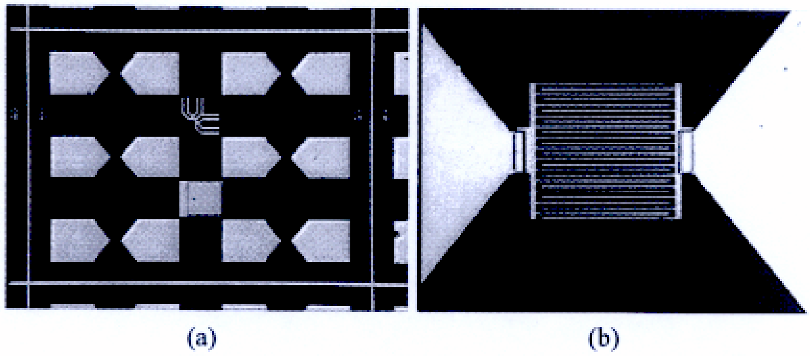


Fig 2. Optical micrographs of: (a) fabricated GaAs MSM photodetectors with finger linewidths of 1, 2 and 3 μm, a fixed finger spacing of 3 μm, a fixed detector area of 100 μm x 100 μm, and a large contact pad of 500 μm x 500 μm and (b) detector area with a finger linewidth of 2 μm.

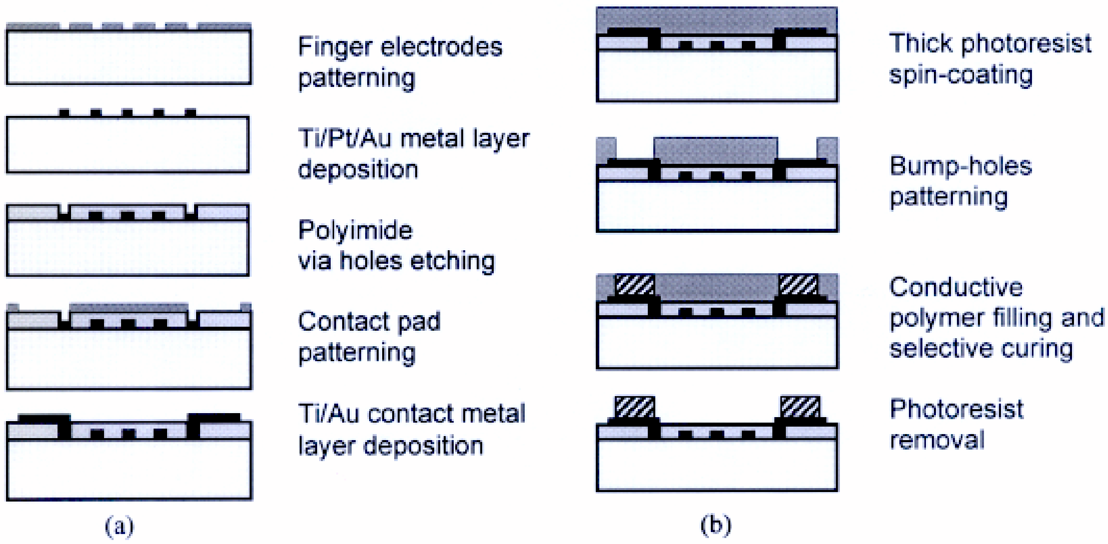


Fig. 3. Summarized fabrication steps for: (a) the GaAs MSMs photodetectors and (b) the formation of conductive polymer bumps on the contact metal pads of the photodetectors.

2.2 Conductive Polymer Bumps

Since GaAs MSM photodetectors usually are sensitive to high temperature processing, the development of low temperature flip-chip bonding techniques is essential in realizing a prototype MOEMS structure for optical I/O couplers. In this work, low temperature flip-chip bonding techniques have been adopted to facilitate the use of conductive polymers to form the electrical interconnections between the photodetectors and MOEMS substrate. Fig. 3(b) describes a summary of fabrication steps for forming the conductive polymer bumps by employing thick photoresist molding process. Thick photoresist (AZ 4000 series) was spin-coated with a thickness of 25 μm and then patterned for bump-holes. After the lithography, thermoplastic conductive polymer materials were applied into the bump-holes. Overflowing materials were immediately squeezed off by a rubber pad. The wafer was cured in a convection oven at 100 °C for 15 minutes. Due to the different curing conditions between the thick photoresists and the conductive polymers, the photoresist molds can be removed leaving the conductive polymer bumps on the contact metal pads. After this selective curing, photoresist molds were stripped away in conventional photoresist stripper, leaving the polymer bumps on the contact metal pads. Following this, the wafer was cured in a convection oven at 150 °C for 1 hour, to achieve a better conductivity for conductive polymers.

The photodetectors were now ready to go for dicing and flip-chip bonding. Fig. 4 shows a micromachined thermoplastic conductive polymer bump, which has a flat surface morphology, with a thickness of 25 μm and an area of 400 μm x 400 μm on a 500 μm x 500 μm gold contact pad. A high bumping alignment resolution of less than 5 μm was accomplished by the use of the thick photoresist molding process described above.

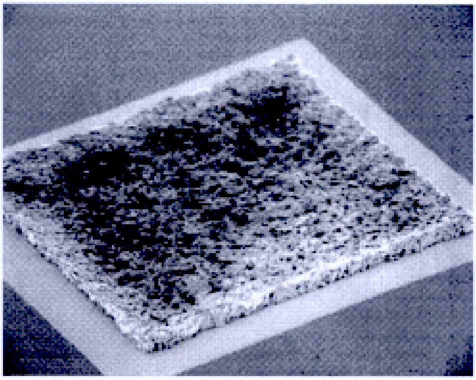


Fig. 4. SEM photograph of a 25 μm high conductive polymer bump (400 μm x 400 μm) on gold contact pad (500 μm x 500 μm).

2.3 Alignment Pedestals and MOEMS Substrate

The top MOEMS substrate was designed for passive flip-chip alignment and conductive polymer flip-chip bonding. A brief summary of the fabrication steps for the top substrate is shown in Fig. 5. Initially Cr/Au (30/300 nm) contact metal pads for the conductive polymer bump contacts were formed by lift-off on a silicon dioxide layer of 1.5 μm, which servers as an insulation layer. Following this, a Ti/Cu (30/400 nm) seed layer was deposited for copper electroplating. Thick

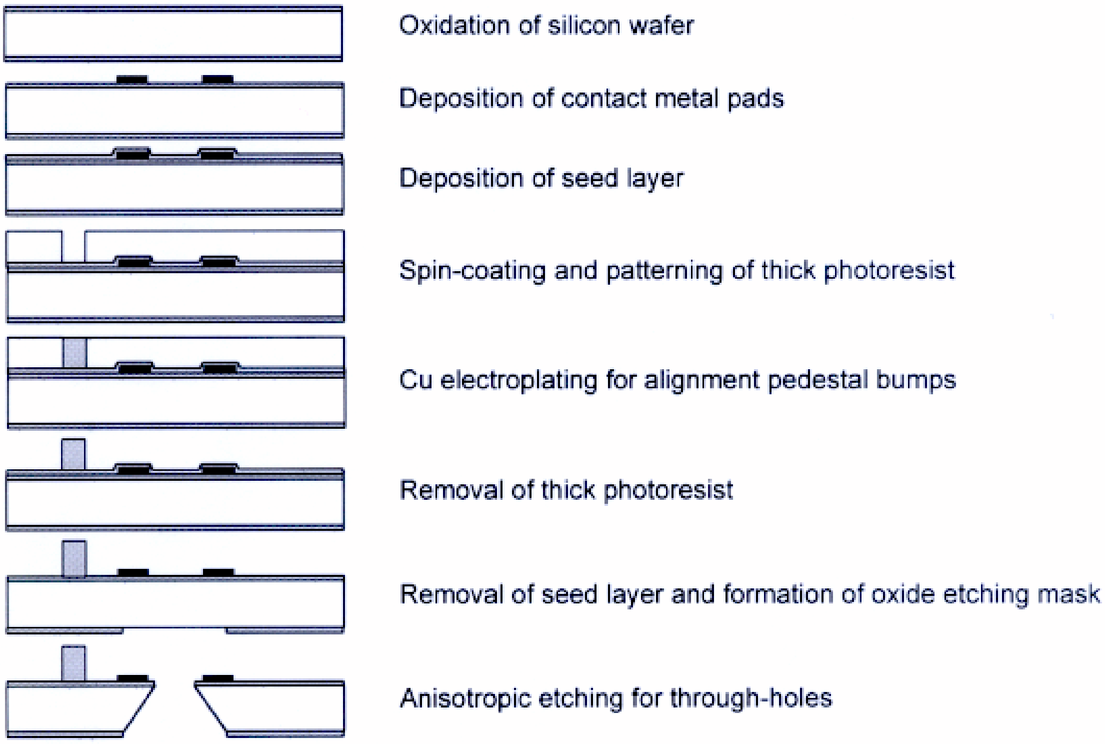


Fig. 5. Fabrication process for the top MOEMS substrate.

photoresist was spin-coated with a thickness of 45 μm and then patterned for side alignment pedestals. The side alignment pedestal bumps were then formed by using copper electroplating technique. Upon the completion of the plating process, the photoresist and plating seed layer were stripped away. The through hole patterns of 700 μm x 700 μm were opened by etching silicon dioxide layer in BHF solution. The through holes were fabricated by etching out from the back side on the (100) silicon wafer in TMAH solutions. As a result, the top MOEMS substrate contained contact metal pads for flip-chip conductive polymer bumps, electrical metal lines for input biases and output signals, alignment pedestals electroplated with copper, and through holes for optical signal paths reflected from the silicon micromirrors. A bottom MOEMS substrate will be micromachined with {111}-oriented silicon micromirrors and V-grooves in KOH or TMAH. By inserting optical fibers through the V-grooves terminated by silicon micromirrors, integrated optical I/O coupler, shown in Fig. 1, will be able to redirect optical signals passing through the top substrate into the photodetectors.

3. FLIP-CHIP PACKAGING FOR MOEMS

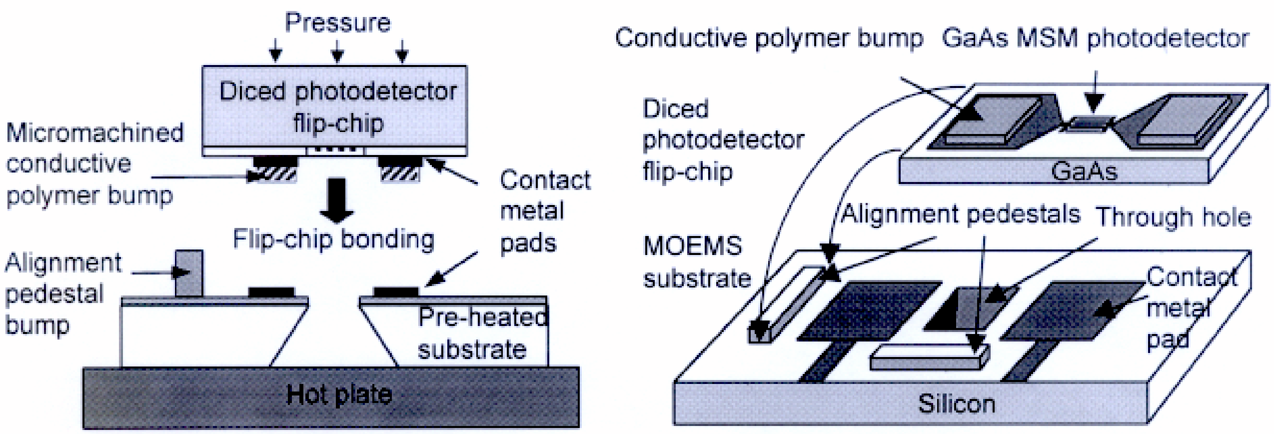
The photodetectors and top wafer were independently fabricated, and then assembled using flip-chip bonding techniques with micromachined conductive polymer bumps and passive alignment techniques with electroplated alignment pedestal bumps. This conductive polymer flip-chip bonding technique allows a low temperature bonding process. Passive alignment techniques are needed for high-efficiency coupling of optoelectronic devices to optic fibers because the techniques enable to reduce packaging time and cost drastically.

3.1 Conductive Polymer Flip-Chip Bonding

Fig. 6(a) illustrates the flip-chip bonding technique for the building of the prototype MOEMS structure. Thermoplastic conductive polymers used in this work possess the property of melting or re-wetting when heated to a specific temperature (150 °C) [7]. After the substrate was pre-heated to approximately 20 °C above the thermoplastic polymer melting temperature, a diced photodetector was flipped, aligned and contacted onto the contact pads of the substrate. The thermoplastic bumps then melted onto the contact pads of the substrate. The mechanical and electrical bonds were established as the substrate cooled below the melting temperature of the thermoplastic materials. To enhance the mechanical bonding strength, a small amount of pressure was applied by placing a weight on the chip.

3.2 Passive Alignment

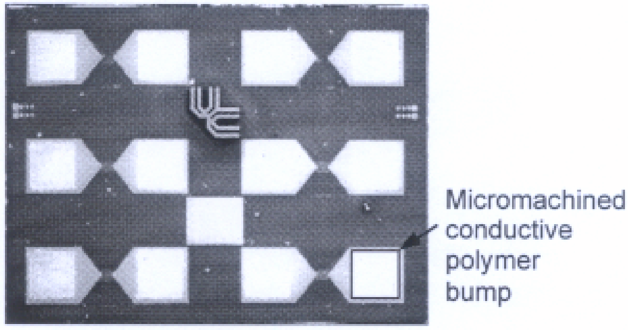
As shown in Fig. 6(b), the flip-chip packaging techniques for MOEMS structure provide a simple passive-aligned flip-chip bonding process. Fig. 7(a) shows a precisely diced GaAs MSM photodetector die with micromachined conductive polymer bumps (400 μm x 400 μm) on the contact pads (500 μm x 500 μm). Fig. 7(b) shows the SEM of the passive-aligned



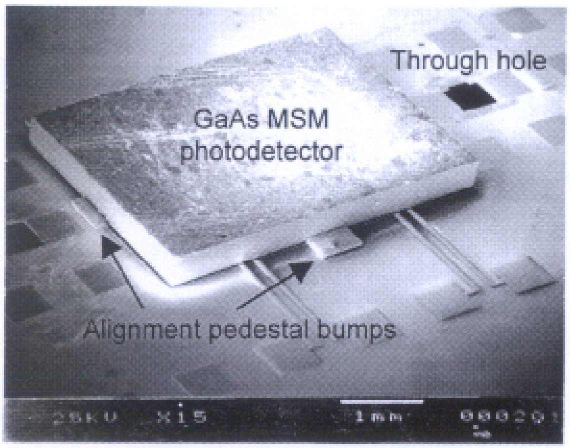
(a) (b)

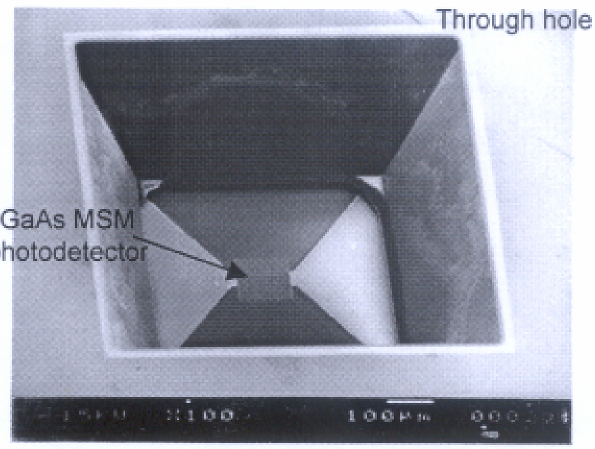
Fig. 6. Illustration of the flip-chip bonding technique for a prototype MOEMS structure: (a) cut view for wafer bonding and passive alignment and (b) schematic view.

flip-chip packaging for the prototype MOEMS structure. The passive alignment between photodetectors and through holes is based on dicing accuracies of flip-chip photodetectors and precise electroplating of side alignment pedestal bumps. Fig. 7(c) is the SEM picture of a finger structure of GaAs MSM photodetector passive-aligned to the through hole on the top MOEMS wafer. To permit the ease of alignment with the optical beam reflected from the micromirror, detector area of 100 μm x 100 μm was designed. When completed, the photodetectors was aligned to the mirror within an accuracy of less than 5 μm.



(a)





(b) (c)

Fig. 7. SEM photographs of: (a) precisely diced GaAs MSM photodetector die with micromachined conductive polymer bumps on the contact pads; (b) the flip-chip packaging for MOEMS with through-holes, alignment pedestal bumps, and contact pad lines; and (c) the finger structure of GaAs MSM photodetector passive-aligned to the through hole on the top MOEMS wafer.

4. EXPERIMENTAL RESULTS

The prototype MOEMS structure for optical I/O couplers involves conductive polymer flip-chip bonding techniques. The electrical properties of micromachined conductive polymer bumps have been evaluated by using a four-terminal method. In addition, the optical properties of GaAs MSM photodetectors flip-chip bonded over the through holes have been characterized by applying optical signals through the holes onto the MSMs.

4.1 Flip-Chip Bonding

A conductive polymer bump sandwiched between the flip-chip and substrate has a certain amount of so-called contact resistance. This contact resistance is obviously an important parameter that impacts the behavior of GaAs MSMs devices. Quantitative determination of the contact resistance in ohms can be evaluated by using a four-terminal method. Using the four-terminal method, the electrical properties of the micromachined conductive polymer bumps have been evaluated. This method was reported in [7] and further detailed descriptions for conductive polymer flip-chip bonding techniques is to be published in another journal articles. The I-V characteristics measured for 25 μm high bumps with various sizes are shown in Fig. 8. The voltage drop was measured as the constant direct current was forced through the bumps up to 50 mA. The contact resistance was simply the ratio of the voltage measured to the current applied. The slopes of the I-V graphs were linear with different driving currents. The resistance reading of 12 mΩ measured for a micromachined 25 μm high bump with 400 μm x 400 μm area was comparable with those of the semiconductor-metal ohmic contact and screen-printed conductive polymer bumps [16], [17]. This conductive polymer flip-chip bonding technique allowed a very low contact resistance (~10 mΩ). Therefore, the signal from the photodetector flip-chip-bonded over the MOEMS structure would not be disturbed due to these polymer bumps.

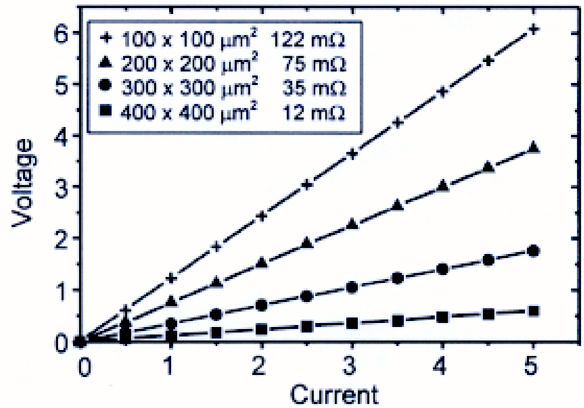
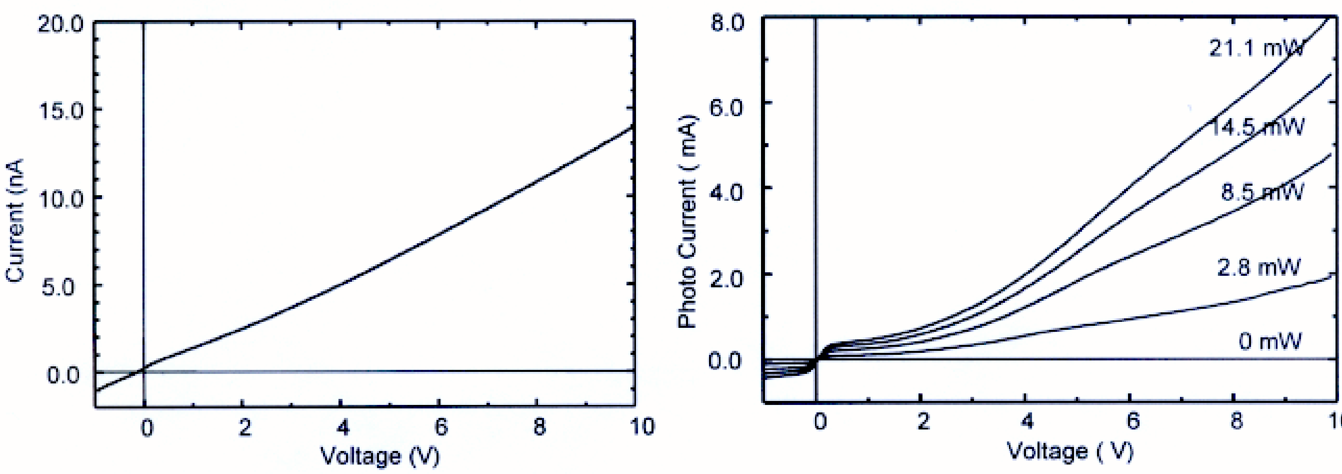


Fig. 8. I-V characteristics measured for 25 μm high bumps with various sizes.

4.2 Photodetectors

The optical properties of GaAs MSM photodetectors flip-chip bonded over the through holes have been characterized by applying optical signals through the holes onto the MSMs. First, the dark current of MSM photodetectors was characterized by evaluating the leakage current between the electrodes in the absence of incident light. The results shown in Fig. 9(a) were measured on the devices with the finger width of 2 μm, a fixed finger spacing of 3 μm, and a fixed detector area of 100 μm x



(a) (b)

Fig. 9. I-V optical characteristics for GaAs MSMs photodetectors flip-chip bonded over the through holes: (a) measured dark currents and (b) photocurrent responses measured with variable laser power.

100 μm. The leakage current was very small and of the order of 10's of nA, which is sufficiently low for a high quality MSM photodetectors. To measure the optical responsivity, the optical output of a short wavelength (870 nm) semiconductor laser was incident onto a detector area of photodetector through the hole. The electrical biases were applied to the photodetector and the photocurrent was measured as shown in Fig. 9(b) with various optical intensities. The responsivity, which is the ratio of the output photocurrent to the input laser power, was 0.66 A/W with the input power of 2.8 mW and the applied bias of 10 volts. The output signals of GaAs MSMs flip-chip bonded with micromachined conductive polymer bumps were not disturbed at all, which results from the low contact resistance between the contact metal pads and bumps. The characterization of silicon micromirrors was already reported in [4]. The final MOEMS structure and optical properties of GaAs MSMs flip-chip bonded over the through holes are under characterization for the optical beam reflected from the silicon micromirrors.

5. CONCLUSIONS

Using micromachined conductive polymer bumps, GaAs MSM photodetectors flip-chip bonded upon the MOEMS structure have been fabricated and characterized. The top substrate embodied through holes, contact metal pads, and side alignment pedestals with electroplated copper to align GaAs MSMs. The conductive polymer bumps have been formed on the contact metal pads of GaAs MSMs using thick photoresist bump-holes as molding patterns. The die of GaAs MSM photodetectors with the micromachined conductive polymer bumps was aligned to the side alignment pedestals within ± 5 μm and flip-chip bonded onto the substrate. This conductive polymer flip-chip bonding technique allowed a very low contact resistance (~10 mΩ) and a lower bonding temperature (~170 °C). This technique also allowed very simple processing steps, comparing to the conventional solder bonding or screen printing polymer bonding techniques. The GaAs MSM photodetectors flip-chip mounted on the top of OE-MCM substrate showed a low dark current of about 10 nA and a high responsivity of 0.66 A/W. The conductive polymer flip-chip bonding technique developed in this work can be applicable to sensor and actuator systems, surface mounting microfluidic systems, bio/chemical micro-total-analysis systems (μ-TAS), optical MEMS, OE-MCMs, and electronic systems [8]. By using bulk-micromachining, conductive polymer flip-chip bonding, and passive pedestal alignment techniques, a prototype MOEMS structure for optical I/O couplers realized in this work shows high potential to use as a fundamental building block in OE-MCMs.

6. ACKNOWLEDGMENT

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