INTEGRATION OF THIN-FILM COMPOUND SEMICONDUCTOR PHOTONIC DEVICES ONTO MICROMACHINED MOVABLE PLATFORMS

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ABSTRACT

The integration of thin film, optical-quality compound semiconductors with micromachined devices enables practical micro-opto-mechanical systems (MOMS). For example, integrated microactuators can be used to position photonic devices for improved coupling in highly position sensitive optoelectronic applications without the use of time-intensive and, therefore, costly manual alignment procedures. We have demonstrated the essential fIrSt step in realizing this goal by placing a semiconductor thin film GaAs/AIGaAs p-i-n structure onto a movable micromachined platform. The thin film photonic device is composed of epitaxial layers grown on a sacrificial AlAs layer which has been grown on a GaAs substrate. After patterning, the devices are separated from the growth substrate by selectively etching away the AlAs layer. The thin film devices are then aligned and bonded to polyimide micromachined movable platforms using a transfer diaphragm technique. The contacts to these devices are run down the legs which attach the platform to the silicon substrate. By applying appropriate voltages, the platform can be electrically actuated up to 2.5 μm vertically and several microns in each horizontal direction while the photonic device is in use. The light weight of the thin film devices does not interfere with the movement of the platform. Applications for this structure include an emitter/fiber or detector/fiber alignment system in which the relatively light emitter/detector is moved instead of the relatively heavy fiber.

INTRODUCTION

The integration of compound semiconductor emitters and detectors with micro machined devices to form *micro-opto-mechanical systems* (MOMS) offers significant opportunities in both sensing and actuation applications. Previous work aimed at MOMS has focused almost exclusively on the micromachining of gallium arsenide or other compound semiconductor materials [1-2]. Although many interesting structures have been fabricated using this approach, there are still several advantages in using silicon: the mechanical properties of silicon are very good; the developed silicon micromachining base is much larger; and the developed silicon circuit fabrication base is also much larger. However, silicon does not efficiently emit light Our approach to MOMS is to fabricate thin fiJrns of compound semiconductor materials which have been grown lattice-matched to an epitaxial sacrificial layer on top of a compound semiconductor growth substrate. Analogous to surface micromachining, the epilayers are separated from the growth substrate by selectively removing the sacrificial layer. The resultant thin filins of optical-quality compound semiconductor devices can be selectively aligned with, deposited onto, and integrated with a variety of host substrates (such as silicon) and micromachined devices, forming a micro-opto-mechanical system which combines all of the advantages of silicon and other micromachining materials with light

There are many applications for MOMS. For example, in the optoelectronic industry, labor-intensive manual alignment of fibers to emitters or detectors is expensive and time-consuming, thus the end cost of fiber optic "pigtailed" products is significantly higher than the sum cost of its components. In the few automatic alignment systems which are currently emerging, the fibers themselves are moved into position while the optoelectronic device is held stationary. These techniques tYPically must employ high-voltage piezoelectric effects because of the relatively large mass of the fiber and the distances moved. A much more economical solution would be an automatic emitter/detector to fiber alignment system in which the relatively light optoelectronic device is moved while holding the optical fiber stationary. We have demonstrated the fIrst steps towards making this solution a manufacturable reality.

PHOTONIC DEVICE FABRICATION

Device Structure

The semiconductor photonic devices used in this work were AIGaAs / GaAs / AIGaAs double heterostructure p-i-n devices. This structure was chosen because it can be employed as either a detector or an infrared emitter by applying a reverse or forward bias, respectively. These high quality single crystal structures were grown lattice matched on top of a sacrificial AlAs layer which had been grown lattice matched to a GaAs substrate. The as-grown layer structure is GaAs (substrate) / AlAs (undoped, 0.2 ~m thick) *f* Alo3Gao7As (n = 3 x 1017 cm-3, 0.5 ~m thick) / GaAs (n < 1014 cm':3, 1.! ~m thick) / ~.3Gao.7As (p = 1.3 X 1019 cm-3, 0.5 ~m thick), as illustrated in Figure 1.

-GaAs Active Layer (1.1 **Ilm)**
AIGaAs n-type Layer (0.5 **Ilm)** ~lAs
Sacrificial Layer (0.5 **Ilm)** GaAs
Substrate

Figure 1 : As-grown semiconductor structure

Georgia Tech Epitaxial Liftoff Procedure

The separation, alignment and bonding of semiconductor thin film devices to dissimilar host substrates is a procedure which has enOrmOUS potential for integrating a variety of materials and functions onto a COmmon substrate. This procedure, named epitaxial lift off (ELO), can be thought of as an extension of surface micromachining, in which the sacrificial layer is epitaxially grown onto a substrate and the structural (device) layer is epitaxially grown on top of the sacrificial layer [3-5].

The first step in fabricating these thin film devices is to deposit and pattern a AuZn *I* Au metallic contact onto the as-grown device epilayers. Although this contact is initially on top of the as-grown device, the device will be inverted onto the platform. This contact will be on the bottom of the device in the final integration and is therefore referred to as the bottom contact

After patterning the bottom contact metal using standard photolithographic techniques and metal etches, the individual devices are mesa etched with a combination of nonselective and selective GaAs *I* AIGaAs etchants. Both 250 ~m x 250 ~ and 100 ~m x 100 ~m devices were fabricated for this work.

This array of mesa etched devices is coated with a protective handling layer of Apiezon W black wax, and the entire structure is immersed in 10% HF to selectively etch away the AlAs sacrificial layer. After separation from the growth substrate, the devices are embedded in the handling layer and the array is subsequently bonded to a transparent mylar diaphragm. The handling layer is then removed with trichloroethane.

Since the polyimide diaphragm is transparent to visible light, individual devices or the entire array can be accurately aligned (currently to within 1 ~m) with respect to features on the host substrate and bonded to the host substrate. After positioning the device either manually or in a mask aligner, a pressure probe is applied to the diaphragm above the device or device array to be transferred. Since the device is inverted during this transfer procedure, both the top and bottom of the device can be processed while the thin film device is supported by either the growth or host substrate. This separation, transfer, alignment and bonding process is illustrated in Figure 2.

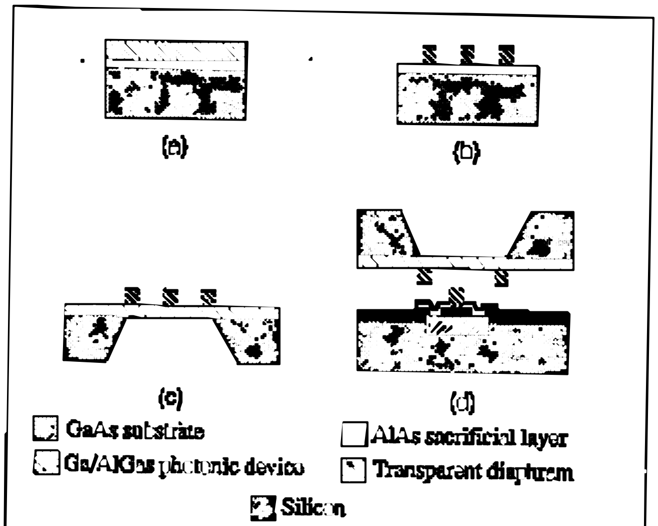


Fig.2: The Georgia Tech Epitaxial Liftoff Procedure. (a) epitaxial layers on growth substrate, (b) define photonic devices, (c) photonic devices transferred to transparent diaphram, (d) align and deposit individual devices.

This technique has been used at Georgia Tech to deposit GaAs and InP based compound semiconductor emitters, detectors and modulators onto arbitrary host substrates. These integrated thin film devices exhibit electrical and/or optical perform~ce which is comparable to or better than their on-wafer counteIparts [6-10].

MICROMACHINED MOVABLE PLATFORM

Movable micromachined platforms have been demonstrated previously by this group [11]. Through the appropriate application of external voltages (typically around 35V), these platfonns can be actuated in both he vertical and lateral directions by as much as 15 ~m and 5 ~m, respectively.

For this work, surface rnicrornachined platfonns were fabricated using standard rnicromachining techniques.. A serie~ of Au actuation strips were defined on an electrically isolated Si wafer. These strips were insulated with a layer of polyin:lide. A 2.5-3.0 ~m copper release layer was deposited on top of the polyirnide, and three layers of polyirnide were spun onto the release layer to fonn the platfonn layer. The actual platfonn shapes and sizes were defined by the top and bottom contact layers subsequently deposited as well as by the transferred chiplet size. Platfonn sizes used in this work were 360 ~m x 360 ~ and 2OO~m x 200 ~m. Both straight and accordion leg platforiris were employed, as were leg widths of 20 ~ and 40 ~m.

INTEGRATION

The transfer diaphragm process was used to deposit the thin film p-i-n devices ontomicromachined movable platfonns. Before release of the platfonns, a 250 ~m x 250 ~m (or 100 ~m x 100 ~m) AIGaAs *I* GaAs *I* AIGaAs thin film device with a bottom ohmic contact was aligned and deposited onto the gold coated 360 ~m x 360 ~m (or 200 ~m x 200 ~m) platfonn. An insulating layer of polyirnide was then spun onto the platfonn and chiplet, and a top contact window to ~e chiplet was o~ned using reactive ion etching (RIE). The top ohmic contact was defined such that it ran down two of the four legs of the platfonn that were not connected to the bottom device contact. The polyimide was then removed using RIE everywhere except where masked by the top and bottom contacts, resulting in the final polyimide platfonn structure with an electrically connected, integrated thin film photonic device. Finally, a window in the top contact was photolithographically defined for optical access to the semiconductor structure. This process is illustrated in Figure 3.

The thin film devices were electrically tested by probing the top and bottom contacts on the pads at the ends of the platfonn legs. The platfonns with integrated devices were then released from the substrate by etching away the cop~r release layer in FeO3 solution.

RESULTS

We have successfully actuated a 360 ~m x 360 ~m and a 200 J!m x 200 ~m polyirnideplatfonn with an electrically contacted 250 ~m x 250 ~m or 100 ~m x 100 ~m chiplet on top (Figures 4 and 5). Through the application of 35 V between the center actuation strip and platfonn, vertical movement was demonstrated. Since the copper release layer was approximately 2.5 ~m thick, this was the range of vertical actuation achieved. Also, horizontal movement was demon~trated through electrical actuation by applying a potential between the platfonn and one of the outer actuation strips.

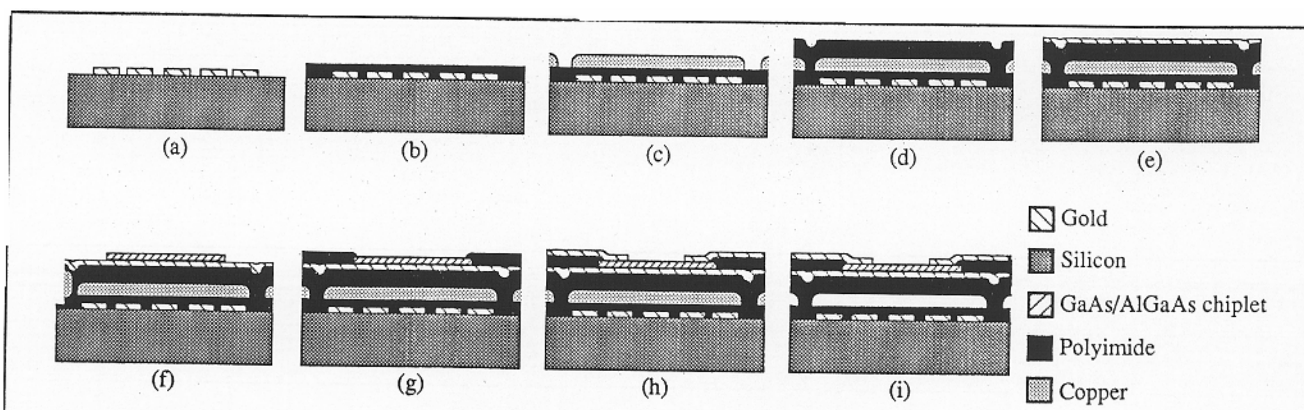
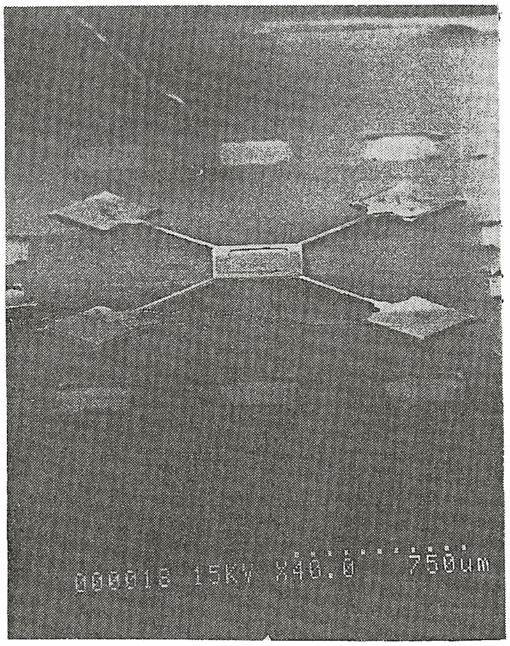
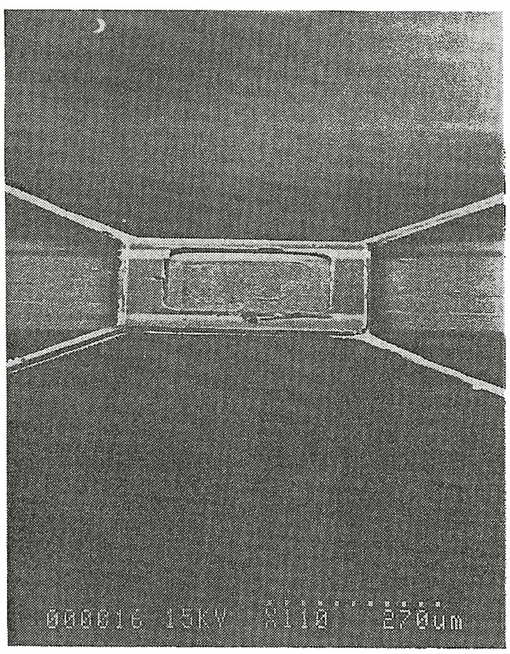


Figure 3 : Processing Sequence : (a) Au actuation strips on insulated Si wafer, (b) insulating polyimide layer spun on, (c) Cu release layer deposited and defined, (d) polyimide platform layers spun on, (e) bottom contact deposited and defined, (f) photonic device "chiplet" deposited onto bottom contact layer, (g) insulating polyimide layer spun on and via opened, (h) top contact deposited and defined, (i) after platform definition, Cu sacrificial layer removed.

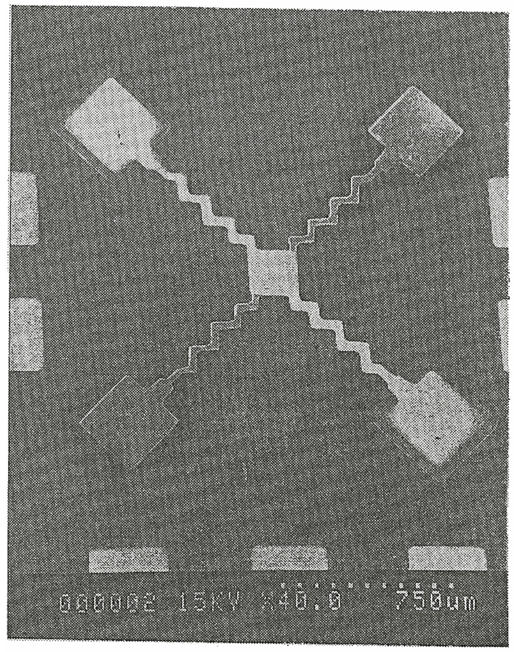


(a)

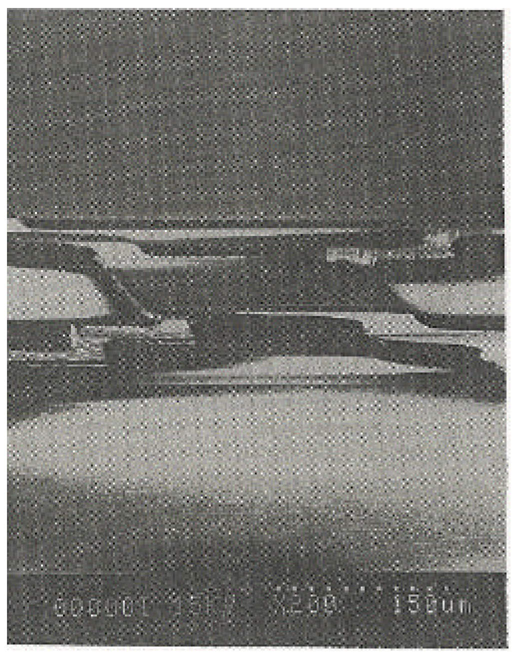


(b)

Figure 4 : SEM photomicrograph of released 360 ~m x 360 ~m straight-leg platform with 250 I.1In x 250 ~m contacted chiplet (a) 40 times magnification, (b) 110 times magnification



(a)



(b)

Figure 5 : SEM photomicrograph of released 360 ~m x 360 ~m accordian-leg platform with 250 ~m x 250 ~m contacted chiplet (a) 40 times magnification, (b) 200 times magnification

We have also demonstrated a working 250 ~m x 250 ~m photonic device atop a platform structure. This device was operated in both forward and reverse bias and exhibited an I-V characteristic comparable to on-wafer p-i-n structures when probed at the base of the platform legs. Also, by focusing light onto the chiplet, a change in the reverse-bias current was seen, indicating that the device was behaving as a detector (Figure 6). The current increased with increasing light intensity, as was expected.

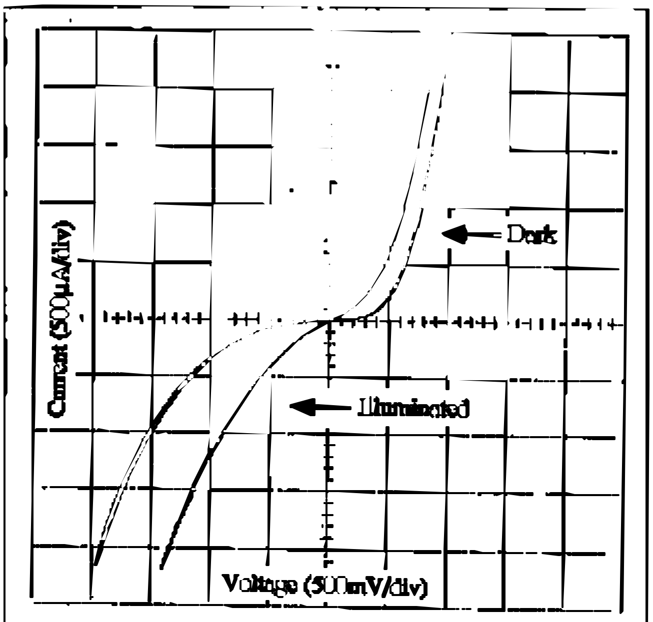


Figure 6 : Current vs Voltage (I-V) curve for 250 µm x 250 µm device on 360 µm x 360 µm platform - dark and under illumination

CONCLUSIONS

We have successfully shown that semiconductor photonic device structures can be combined with standard micromachined devices resulting in a manufacturable micro-opto-mechanical system. These devices offer significant opportunities in both sensing and actuation applications. Through the use of the Georgia Tech epitaxial liftoff procedure, thin-fIlm semiconductor devices were separated from their substrates and aligned onto an electrically actuated polyirnide micro machined movable platform, forming a complete system integrating optical and micromachined components. These techniques take advantage of the most useful properties of each material system without sacrificing either mechanical or optical performance.

We have demonstrated the first step towards an integrated emitter/fiber or detector/fiber alignment system. In this system, the relatively light photonic device is moved rather than the relatively heavy fiber, meaning that less actuation force is required than in other fiber alignment systems. Through the use of the Georgia Tech transfer diaphragm process, thin fIlm compound semiconductor photonic devices can be placed directly onto micromachined movable platforms. The result is a highly manufacturable and innovative method for aligning a photonic device to a fiber without the use of labor intensive and costly manual positioning techniques.

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