Promise and Progress of GaAs MEMS and MOEMS

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Abstract

We discuss progress and prospects for compound semiconductor MEMS and MOEMS, in particular GaAs-based devices. Various applications, such as optical switching, sensors and RF will be highlighted with a particular focus on distinguishing characteristics of compound semiconductors over silicon structures.. We present our work on a 1x2-waveguide switch. Data on fabrication and performance of this GaAs/AlGaAs device will be presented. Devices are predicted to switch in less than 40 μsec. Switching voltages of 15 V and propagation losses of 0.8 dB/cm were measured

In the recent past silicon MEMS and MOEMS have undergone a period of explosive growth, both in terms of academic and commercial interest. While silicon has played a dominant role, there is an increasing interest in compound semiconductor approaches. This is driven largely by emerging optical and sensor applications. Optical switching represents one rapidly growing area of MEMS. While silicon approaches abound, including waveguides [1] and tip-tilt mirrors [2], increasingly alternative materials are finding use. In the area of displays, the most successful approach to date utilizes silicon CMOS electronics, but the opto-mechanical element itself is made of aluminum [3]. A number of sensing applications as well as those combining on chip sources and detectors are not possible at all in the silicon material system.

Use of compound semiconductor for realization of MEMS and MOEMS addresses several problems. Because these are usually epitaxially grown, they are monocrystalline, have atomically flat interfaces and extremely well controlled thickness, unlike polycrystalline materials (such as polysilicon). Also, stress of epitaxial films is much more accurately controllable, (by control of the lattice mismatch) than that of polycrystalline materials (usually controlled by annealing cycles). Most importantly, the right choice of a combination of compound semiconductors, such as GaAs-based or InP-based material system, allows for direct incorporation of optical functions into mechanical structures. This is because compound semiconductors are direct (unlike Si) and have traditionally been used for a variety of active and passive optical elements. Another advantage of compound semiconductors for MEMS/MOEMS applications is the very rich chemistry, which can be used for release of the mechanical layers. There are few material combinations and chemical etches applicable to fabrication of Si MEMS/MOEMS (such as use of SiO_2 or BPSG as a sacrificial layer and HF or BOE as chemical etches). In the compound semiconductor arena there are numerous combinations of materials and release etches which can result in MEMS/MOEMS structures [4]. Finally, the zinc blende structure of most common compound semiconductors allows for piezoelectricity as a result of lack of center of symmetry (in contrast to silicon). This property leads to interesting sensing applications. General skepticism surrounding mechanical properties of compound semiconductors is largely unfounded. While not as strong as silicon, compound semiconductors are sufficiently robust for most MEMS applications [5] and are in fact stronger than highest quality steel.

Applications combining active optical functions with mechanical functions have benefited the most from use of compound semiconductors. Uenishi et. al. [6] have demonstrated monolithic integration of a GaAs-based micro cantilever beam with two laser diodes. The beam vibrated in the plane of the wafer upon excitation from the laser diode operating in the DC regime. The vibration of the cantilever in turn modulated the laser diode output of the second adjacent laser diode.

Another demonstration of combined active optical and mechanical functions on chip involves tunable vertical surface emitting lasers (VCSELs). These devices rely on epitaxially grown quarter wave stacks above and below the

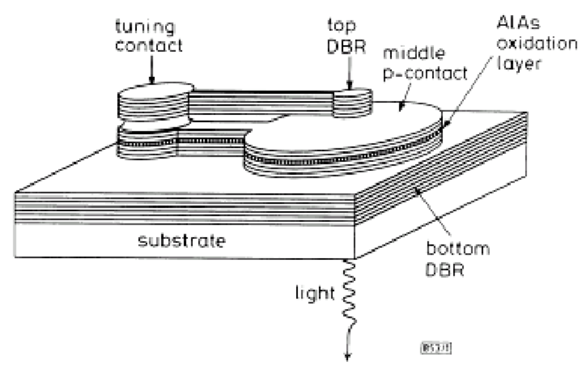


Figure 1 Schematic diagram of a micromechanical tunable VCSEL [7]

active region to form the laser cavity. Several groups have demonstrated tunability [7,8], by suspending the top

quarter wave stack as a cantilever and modulating the air gap electrostatically.
This is a particularly exciting application of compound semiconductor MOEMS, since these devices are finding applications in the rapidly growing telecom and datacom industries. With the increasing emergence of wide division multiplexing (WDM) as a communication protocol of choice, the need for tunable VCSELs is growing. Similarly, tunable resonant cavity photodetectors have been demonstrated in both GaAs [9] and InP [10] based systems. The cavity is tuned actuating the top mirror and modulating the air gap, but the active region is reverse biased to collect photogenerated electron-hole pairs.
Another WDM application of micromachined compound devices involves passive optical components, such as filters. These are based on modulating the air gap between two high reflectivity mirrors, in a manner similar to the tunable sources and emitters described above [11]. One example of such a structure is shown below, in Figure 2.

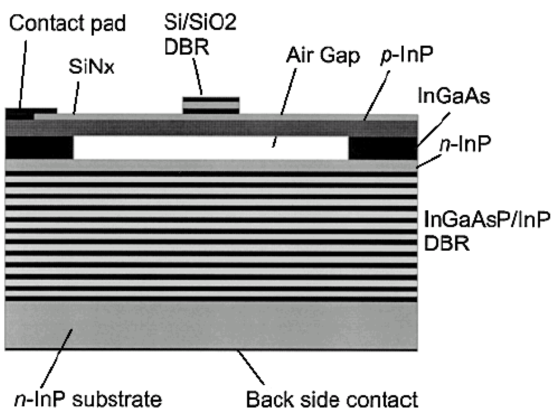


Figure 2 Schematic cross section of InP-based tunable Fabry-Perot filter [11]

Compound semiconductor micromachining is also finding applications in the field of monolithic microwave integrated circuits (MMICs) as a means of realizing discrete passive components with decreased parasitics and losses. For example, a micromachined planar spiral inductor, with the strips suspended individually, has been fabricated in standard GaAs high electron-mobility transistor monolithic-microwave integrated-circuit technology through mask-less front-side bulk micromachining [12]. The air-gap underneath the device and between the strips significantly reduces shunt and fringing parasitic capacitances, consequently increasing the performance and operating frequency range. Figure 3 shows a scanning electron microscope micrograph of a suspended planar spiral inductor.

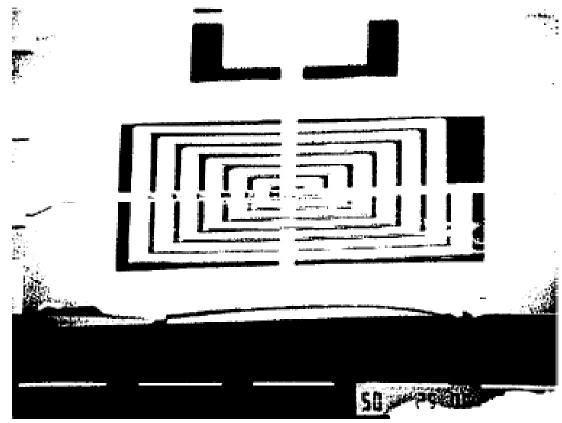


Figure 3 Scanning electron microscope micrograph of a suspended planar spiral inductor [12].

Photoelastic properties of compound semiconductors have found application in interferometric pressure sensors, for example [13].
Infrared bolometry has been demonstrated using broadband gold black absorbers positioned on micromachined AlGaAs membranes of high thermal resistance. AlGaAs compounds are more suitable for realization of good thermopile devices then silicon materials, because their Seebeck effect, electron mobility and thermal resistance are higher. Thus excellent

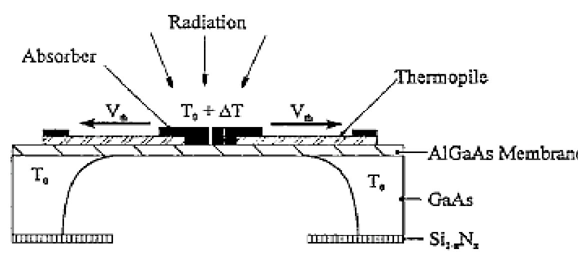
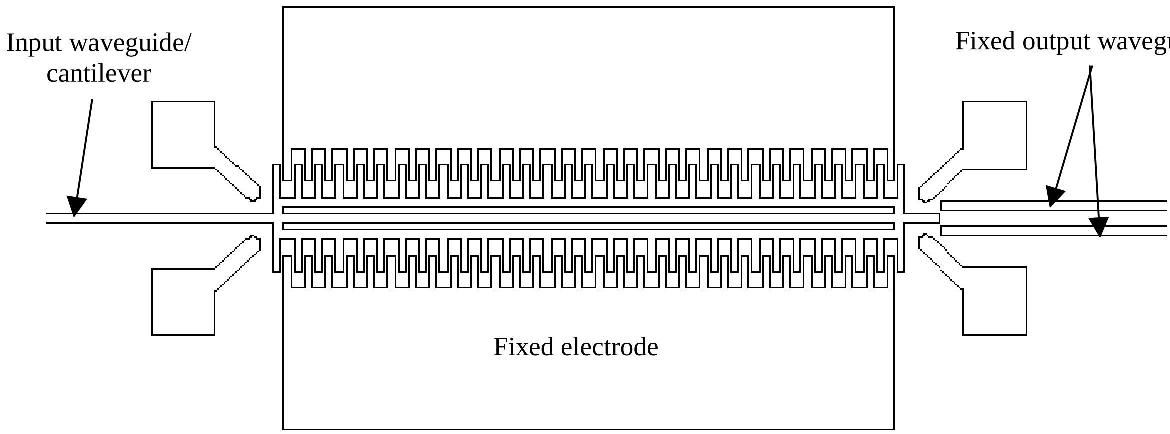
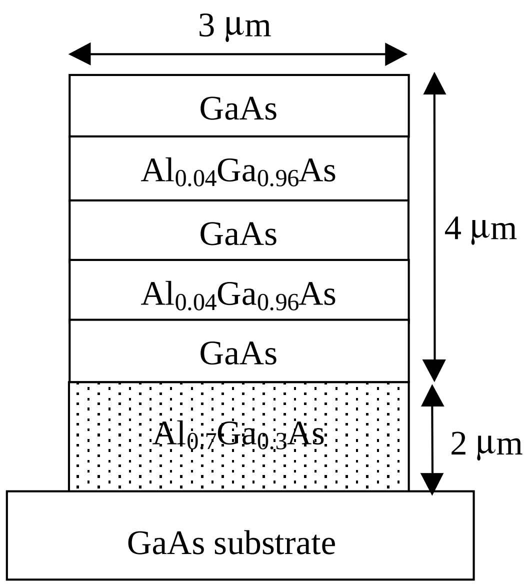


Figure 4 Cross section of a AlGaAs-based infrared bolometer [14]

bolometric infrared sensors have been realized using suspended AlGaAs membranes [14]. Figure 4 shows schematically a cross section of such a device.
In this paper we describe 1x2 waveguide switch which is also a cantilever, fabricated in GaAs-based materials. The switch can be cascaded into 1xN structure. This type of device can enable several possible applications including a low-power, wide-bandwidth, high-resolution space-borne array antenna using true-time delay (TTD), nonvolatile mechanical memory based on latching waveguide switches. It is also possible to integrate this type of structures with active sources and detector and use them for detection of sub-micron displacements.
The layout and layer cross sections of the waveguide are shown schematically in Figure 1a and b, respectively.



(a)



(b)

Figure 1 (a) Schematic top view of the 1x2 waveguide switch (b) Cross sectional view of the layer structure comprising the waveguide. Shaded area indicates sacrificial layer

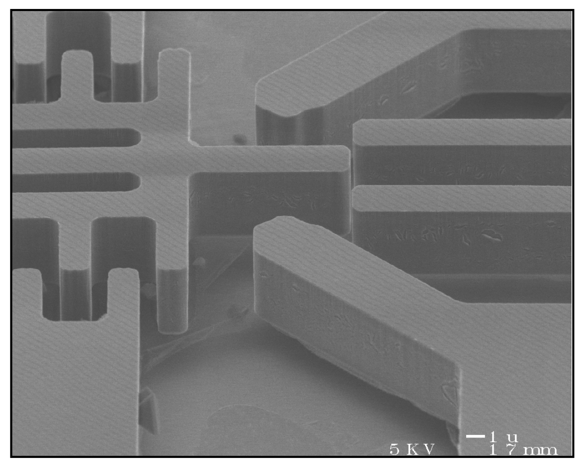


Figure 2 Scanning electron microscope view of the switch

The waveguide consists of 4 μm thick GaAs/AlGaAs layer, while the release layer is composed of 2 μm of $Al_{0.7}Ga_{0.3}As$. Metal contacts are deposited on a planar substrate prior to waveguide definition. Then 3 μm wide waveguide is defined by reactive ion beam etching (RIBE). Photoresist is defined on the areas to be protected against release and sacrificial layer is removed by a HF-based wet etch. After photoresist removal, devices are sublimation dried. Figure 2 shows a scanning electron micrograph (SEM) of a released structure.

As noted previously, several release etch combinations are possible with an appropriate choice of materials, some of them much more selective than then those available for Si-based materials [4]. Here, we have chosen AlGaAs layer to be sacrificial and HF-based chemistry, but InGaP sacrificial layers are also attractive, because of its relative environmental inertness. Release chemistry based on HCl is appropriate in that case.

Actuation is accomplished by electrostatic means, by application of bias between the movable waveguide and static electrodes. This results in 4 μm motion of the cantilevered waveguide in the plane of the wafer

Preliminary mechanical models indicate switching speeds of less than 40 μsec at applied voltages of 25V can be expected. Optimization of drive signal and appropriate device design may lead to speeds in the 10 μsec regime. Experimental switching voltages near ~15 V have been measured in most devices, with some switches operating as low as 7 V.

Waveguides are designed for single mode operation at 1.32 μm, although simulations indicate that up to four optical modes may exist. Optimization of the launch conditions is expected to result in propagation of a single optical mode. Theoretical models predict waveguide loss to be less than 0.5 dB/cm. Experimentally measured end-to-end loss, obtained by wavelength detuned Fabry-Perot technique, was found to be on the average 0.8 dB/cm^{-1}. This does not include waveguide insertion loss.

Compound semiconductors, especially GaAs are finding increased use in MEMS applications. The ability to integrate microelectronic, optical and micromechanical functions in a monolithic or post-processed manner on a single substrate is very attractive for micro-system integration.

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