Van der Waals Bonded III-V Films for Optoelectronics

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We describe the use of epitaxial lift-off for optoelectronics. With this technique, a high quality film of GaAs- or InP-based semiconductor is detached from its growth substrate and bonded, through van der Waals forces, to a new substrate with more favorable properties than the growth substrate. Photodetectors and transistors with good performance have been made with these transferred films, with all of the fabrication done after the transfer to obtain accurate alignment.

INTRODUCTION

One of the challenges of optoelectronics integration is to combine monolithically a variety of optical and electronic components. Unlike purely electronic integration, such as in a typical silicon integrated circuit, optical components are best made from a diversity of materials having different, and sometimes conflicting, processing and structural requirements. While great progress has been made in the integration of various combinations of optoelectronic components (lasers, detectors, transistors, optical waveguides and optical modulators) using III-V semiconductors, this approach requires complex epitaxial growth and device processing techniques, and it is debatable if this approach will advance beyond the research stage. A more fundamental question is the degree to which the performance of the optoelectronic circuit is compromised by requiring each of its components to be made from a single lattice-matched material system rather than from the material that would give the best performance. A diametrically opposite approach, therefore, is to make each component separately using the best technology available for it, and then assemble the necessary components to form a hybrid circuit. The objections to this approach are in the introduction of parasitics that will degrade the performance at high frequencies and in the cost and variability of assembly. Even a misalignment of about a micron can significantly degrade the coupling of light to an optical component, so assembly is often time-consuming and require active alignment (i.e., monitoring the performance during assembly).

A compromise between these two extremes is to use the best technology available for each device, but to develop assembly techniques that will introduce few parasitics and be low cost. The factors that potentially give monolithic integration an advantage in these areas are the use of thin film microfabrication techniques to give compact, low parasitic interconnects, the use of photolithography for accurate alignment, and the simultaneous fabrication of devices on a wafer. Taking advantage of these factors require a flat or nearly flat substrate. In this paper, we describe a technique, which we call epitaxial lift-off or ELO, of transferring large areas (up to several square centimeters) of extremely thin semiconductor III-V films (down to 20 nanometers) to a new substrate. The films contain all of the layers necessary for the device to be made, yet are thin enough that they do not perturb the flatness of the substrate, so that standard microfabrication techniques, including photolithography, can be employed. To minimize the thickness of the film, no intentional adhesives are used and the film is bonded directly on the substrate.

In this paper, we first will describe the ELO process. Examples of the use of ELO for optoelectronics are then described. Finally, we conclude with a discussion on when ELO can have a significant technological advantage over other methods.

EPITAXIAL LIFT-OFF

This technique depends on the selective removal of the device layers from the growth substrate. The two semiconductor systems of primary interest for optical communications, GaAs and InP, require somewhat different processing steps because of the differences in the selective etches available. In the GaAs system, a thin sacrificial layer of AlAs that is lattice matched to GaAs is used (1)(2), while in the InP system, the substrate is etched away using a lattice matched $In_{0.53}Ga_{0.47}As$ etch-stop layer that is grown below the device layers (3). In both cases, the wafer with the appropriate device layers and lift-off layer is covered with Apiezon W wax that provides the mechanical support once the device layers are free of the substrate (Fig. 1). To etch the sacrificial AlAs layer by selective undercutting in the GaAs case, the waxed sample is immersed in hydrofluoric acid for several hours, depending on the size of the sample; to selectively etch the InP substrate, it is immersed in hydrochloric acid for about an hour. Once freed from its growth substrate, the waxed semiconductor film is rinsed in de-ionized water and placed on the new substrate while wet so that it can be aligned by sliding it on the water layer. The precise placement of the film is not critical since we depend on the subsequent photolithography to determine the device placement. Once aligned, the water is gently squeezed out and blotted up and the semiconductor film is allowed to dry overnight with a small weight on the film. During the drying process, water escapes to the edges by a Poiseuille flow and the gap between the semiconductor and substrate decreases until the short range, attractive van der Waals forces can hold the two together. In some instances, the overnight drying has been followed by a vacuum bake at 300° C for several hours, but with no systematic change in the adhesion. For the technique to work, it is important that both surfaces are hydrophilic, i.e., the water wets both surfaces.

When the new substrate is transparent, we observe no Newton rings through the underside except around occasional trapped particles, indicating the two are in close contact over almost all of the area. Cross-sectional transmission electron microscopy indicates there is an interfacial layer typically 10-20 nm thick between the film and the substrate (4)(5). The composition of this interfacial layer is not known, but it is amorphous (4) and has a low index of refraction (5). This layer almost certainly includes the native oxides from the underside of the ELO film and from the topside of the substrate, but these do not account for its total thickness. Other possible components of the interfacial layer may be additional oxides or hydroxides of the ELO film formed during its contact with water, trace impurities precipitating from the water or small amounts of organic compounds leaching from the wax and redepositing at the interface.

The adhesion is not particularly strong. For example, the film does not survive the "Scotch tape test," and when it is etched into small mesas, many of the mesas come off (6). The film before the etch may adhere well only in some places yet the film as a whole is adherent; but after the etch, it is essential that each mesa be adherent. Nevertheless, the film adhesion is sufficiently strong to survive several processing steps, so we use these first steps to improve the adhesion (7). The mesas are "taped" to the substrate with a deposited metal or dielectric film. This is accomplished by first etching holes in the film to the substrate, depositing metal or dielectric so it straddles the film and substrate, and finally etching the mesas so that they are held down by the metal or dielectric. To keep the number of steps down, the metal or dielectric films are normally part of the device.

The adhesion greatly improves if the film is transferred onto a substrate that reacts chemically with the film; an example of this is GaAs on a palladium-coated substrate where the palladium reacts with the GaAs to form Pd_4GaAs even at room temperature (8). However, the presence of even a thin metallic bonding layer is detrimental for optical waveguides and this method cannot be used for these applications.

Another processing concern is the effects of thermal cycling. Microscopic pockets of trapped water or other contaminants trapped under the ELO film can cause a blister or crater to form when heated to modest processing temperatures (>300° C). Although such pockets may be few in number, the effect of the blisters or craters is over a large portion of the film. We improved the cleanliness to decrease the particle count and etch the films into mesas before any heating step to counteract this effect. Such an etch, which is normally done for many devices and so does not add to the processing complexity, removes most of the film and thereby reduce the number of potential blister sites. Moreover, it provides a short (tens of microns rather than millimeters) path for vapors to escape and it localizes the damage from a blister to one mesa.

EXAMPLES OF ELO DEVICES

We give examples of devices made on ELO films on substrates other than the growth substrate. The first is an $In_{0.53}Ga_{0.47}As/InP$ p-i-n photodetector that is used to detect light in the wavelength range of interest for optical fiber communications (1.3 to 1.6 μm). Light from fibers will be coupled into channel waveguides where various switching, splitting and modulation functions can be done. Since in certain applications, it is necessary to detect the light in the waveguides, we have used ELO to integrate photodetectors with waveguides. The waveguides are made from soda-lime glass or lithium niobate, materials with excellent optical properties but which cannot be used to detect light and which are unsuitable substrates for growth of high quality semiconductor. The second device is a GaAs field-effect transistor with a Schottky barrier gate (MESFET) of interest for high speed electronics. A preamplifier made from MESFETs placed next to a photodetector would form a complete receiver.

Photodetectors

We have made photodetectors on glass and lithium niobate waveguides. The ELO film with the detector layers is transferred to the waveguide substrate after the waveguides have been made, and the film is then used to make detectors. It is important for high speed considerations that the detectors be as small as possible to keep the capacitance low, so they should not be much wider than the 7 μm width of the waveguides. By doing post-transfer processing, it is easy to obtain narrow detectors that are well aligned to the waveguides. A typical processing sequence is shown in Fig. 2. The dark current of the ELO p-i-n detector was about 70 nA, compared to about 10 nA for detectors made directly on the growth wafer. The dark current of the ones made on the growth wafer increased to about 70 nA when they were lifted-off (7). This indicates there is a modest change in the device due to the ELO, although these values of dark current are still acceptable for many applications. The speed of p-i-n detectors, 13 GHz bandwidth for the geometry tested, was shown to be unaltered by the ELO process (9).

To characterize the coupling of light from the waveguide to the detector, we measured the decrease in photocurrent along a series of detectors on the same waveguide. There is an exponential decrease because of the loss of light from the upstream detectors. In the case of a GaAs detector on lithium niobate, we obtain an absorption coefficient of 30 cm^{-1}. Mathematical models of the structure suggests the absorption ought to be almost twenty times higher, with little sensitivity to model parameters within a physically reasonable range. The only realistic change to the model that can have such a major effect is the presence of a low index of refraction material between the GaAs and the lithium niobate. The model predicts that only a 10 to 30 nanometer thick layer (the exact thickness of this layer depends on its index of refraction) is sufficient to account for this difference. Cross-section transmission electron microscopy indeed shows that there is an amorphous layer in this thickness range in the interface.

The optical coupling can be improved in one of two ways without the need to eliminate this interfacial layer. One is to deposit a dielectric on the waveguide so that the interface comprises of this deposited layer and the inherent amorphous layer. With the proper choice of index of refraction and thickness for the deposited layer, it will "impedance match" the transition from the waveguide to the detector and improve the coupling. Another way, which is much less process-sensitive, is to form half the waveguide in the substrate, put down the detector, and complete the waveguide by depositing additional dielectric for the top half of the waveguide (10). In this way, the detector is buried in the core of the waveguide and much stronger coupling is achieved.

Transistors

To complement the photodetectors, we have also made post-transfer fabricated GaAs MESFETs (11)(12). While these were made on silicon wafers as a demonstration of ELO as an alternative to GaAs on Si heteroepitaxy, the substrates could have just as easily been an optical material. The GaAs was lifted-off onto either a thermally grown oxide or a plasma enhanced chemical vapor deposition silicon nitride layer rather than the bare silicon substrate for electrical isolation of the MESFETs from the substrate. After etching the GaAs to define the MESFETs, each MESFET becomes an island and the isolation between devices is far superior to that obtained on the growth wafer. The resulting device structure is very similar to that for silicon-on-insulator. For example, the leakage currents at 50 V is still sub-picoampere, whereas typical leakage currents under the same conditions on the growth wafer is nanoamperes and above. Furthermore, sidegating (13), which is the unwanted modulation of a MESFET by a nearby one mediated by substrate traps, is largely eliminated with the oxide or nitride layer. This dielectric also is important for minimizing the capacitance of interconnect metals and bonding pads because its dielectric constant is smaller than that of semiconductors.

The DC and RF performance of these MESFETs are comparable to those made directly on the growth wafer. The peak extrinsic transconductance is 135 mS/mm and the saturated drain current I_{dss} is 130 mA/mm. For a 1.3 μm gate length transistor, the current gain cutoff frequency f_t is 12 GHz and the maximum frequency of oscillation f_{max} is 13.5 GHz, which are typical for this gate length. The Schottky barrier gate leakage current, however, is somewhat higher for ELO devices. Though it is not enough to adversely affect the DC drain characteristics, it may have an effect on the noise characteristics of the transistor.

CONCLUSIONS

We showed that reasonably good transistors and photodetectors can be made using the ELO technique. Although one can, in principle, place these devices on a variety of substrates like with any other bonding technique, one needs to look from a broader viewpoint: what would be the advantage of having placed the device directly on the new substrate, and could the same functionality and performance have been accomplished another way? For example, if one is interested only in electrical connectivity, then ELO is not the method of choice, especially with low density connections where solder bump bonding can be used. We have considered cases where we believe there is a significant advantage to using ELO. In the case of the photodetectors, the light in the waveguide can interact with the detector because the gap can be made small, or better still, the detector can be buried within the core of the waveguide. Both are made possible from the thinness of the ELO film. And in the case of the MESFETs, the electrical property of the growth substrate is a limitation and ELO allows one to use a substrate that improves the device isolation, in the same way that silicon-on-insulator technology does for CMOS.

Like any technology, ELO has its competition. One must carefully weigh the strengths and weaknesses of each technique before deciding which is best. The areas that we believe ELO can have a significant impact are those where the thinness of the film plays a role, for example, to promote some interaction with the substrate or to allow the use of thin film interconnections.

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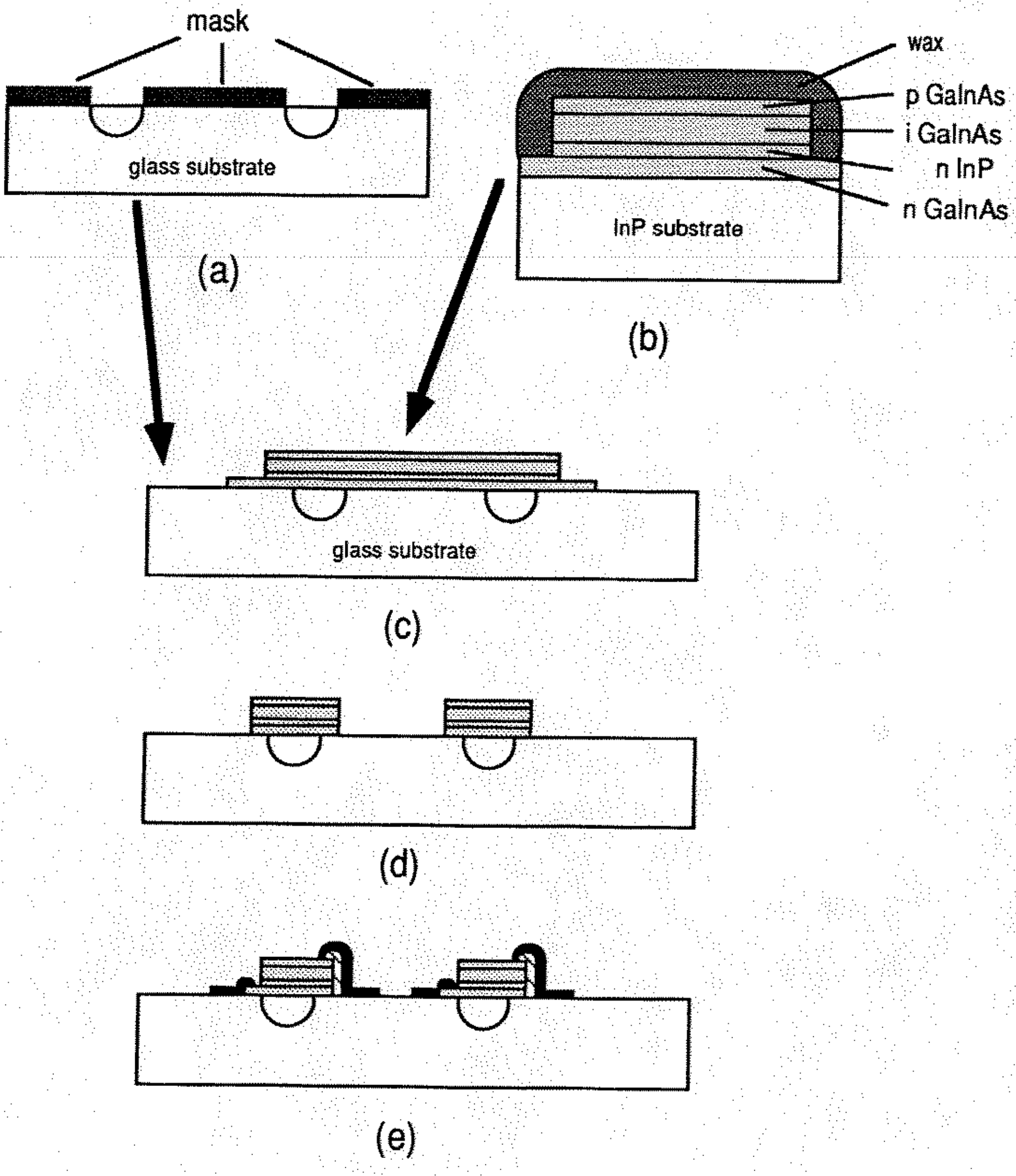

Fig 2: Schematic of device processing sequence for photodetector on waveguide. (a) Waveguides are made on a glass substrate by ion exchange through a mask. (b) The detector layers are separated from the growth substrate and van der Waals bonded to the glass (c). The film is then processed into photodetectors (d) that are aligned to the underlying waveguides with lithographic precision (e).

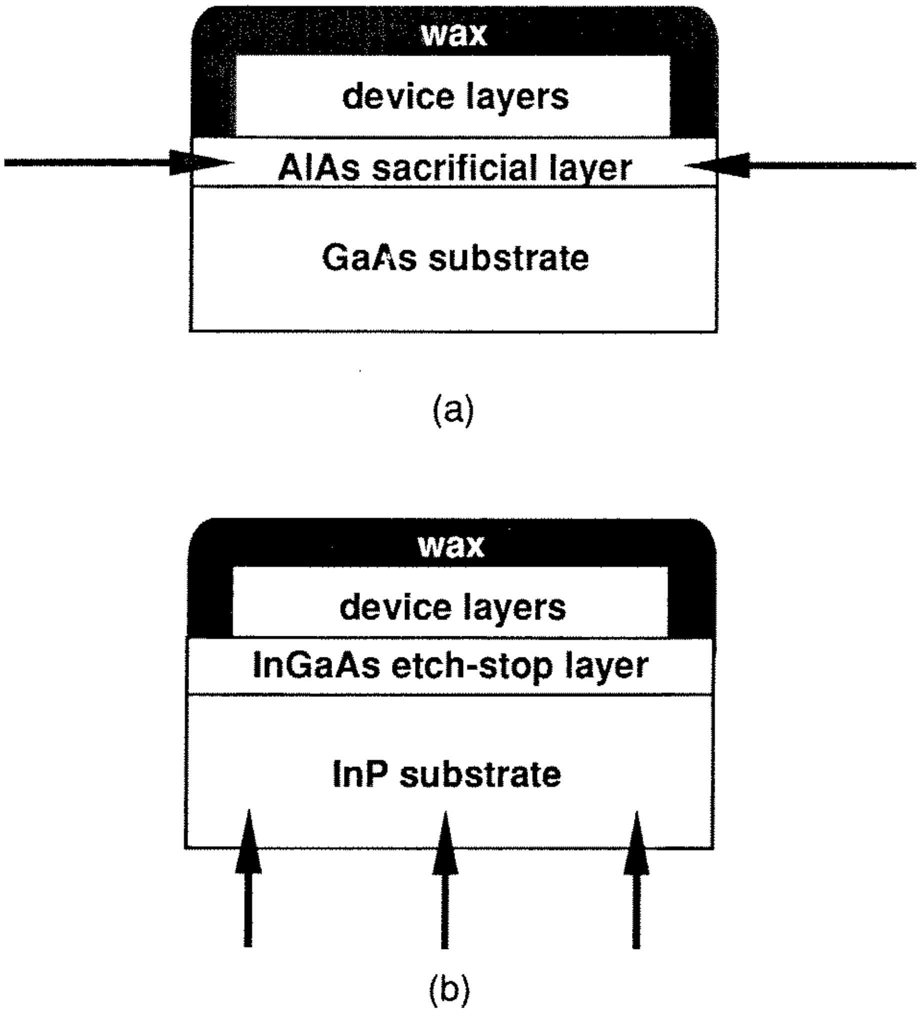

Fig. 1: Schematic of epitaxial lift-off geometry for (a) GaAs-based material and (b) InP-based material. Arrows show the direction of attack for the selective etchant. For GaAs, HF selectively etches the AlAs sacrificial layer while for InP, HCl selectively etches the substrate and stops at the etch-stop layer which can be selectively etched afterwards. The wax protects for the device layers during the etch and supports them once they are freed from the substrate.