EPITAXIAL LIFTOFF

Epitaxial liftoff (ELO) is a process for removing an epitaxial film from its original growth substrate and then subsequently depositing that film on a new host substrate or superstrate. This permits the possible reuse of the original substrate and the fabrication of ultrathin devices. Attractive applications of this process include creating thin solar cells for space applications, components of a tandem solar cell structure, optical modulators, lasers, detectors, and a variety of combined silicon and III–V optoelectronic devices. For space solar cells, the specific power ratio (power output per kilogram) is a critical factor and the epitaxial liftoff procedure permits the design of a very thin solar cell, possibly less than 5 μm, bonded to a coverglass superstrate resulting in a high specific power ratio. For the other applications, the thermal or mechanical properties of the new host substrate or device structure provide a critical advantage. The transparency of the new host substrate is an essential feature for optoelectronic devices.

METHODS OF EPITAXIAL LIFTOFF

Three approaches have been used to separate epitaxial films after growth on single crystal substrates: mechanical cleaving, selective chemical etching (peeled film), and sacrificial substrates. Mechanical cleaving was developed as a CLEFT (cleavage of lateral epitaxial films for transfer) procedure (1). CLEFT required epitaxial overgrowth by organometallic chemical vapor deposition (OMCVD) on a substrate masked by silicon oxide (sometimes covered by silicon nitride) to form a pattern of narrow stripes exposing the substrate. The lateral growth was due to surface-kinetic control for a two-dimensional growth geometry. The lateral growth takes place until the growth fronts originating from within adjacent openings merge to form a continuous layer, after which conventional vertical growth continues until the layer reaches the desired thickness. The surface layer is then bonded to a glass substrate, or other host substrate, and then physically cleaved from the substrate. Factors that were critical to a successfully cleaved device included substrate cleanliness, OMCVD growth conditions, and the orientation of the cleavage plane. In some cases, the cleavage plane and growth plane may be mutually exclusive, prohibiting the use of CLEFT for some devices. Reuse of the substrate has been demonstrated in CLEFT but requires a significant effort to repolish and remask. This activity reduces the economic benefit of substrate reuse.

Selective chemical etching as a means of "peeling" thin films was first demonstrated by the fabrication of a p on n GaAs solar cell on a 5 μm thick $Ga_{0.3}Al_{0.7}As$ layer grown by liquid phase epitaxy (LPE) on a GaAs substrate (2). The GaAs device structure was covered with a black wax film and the entire wafer was soaked in an aqueous hydrogen fluoride (HF) etchant solution. The etchant solution selectively dissolved the $Ga_{0.3}Al_{0.7}As$, allowing the solar cell attached to the wax to be peeled off the GaAs substrate for placement, in this case, on an aluminum substrate. The wax provided the support for the peeled film after separation from the GaAs substrate. The major difficulty in applying this technique was the formation and entrapment of hydrogen gas, formed as a reaction product of the etching process within the etched channel. The trapped gas diminished further etching and caused cracking in the epitaxial film. A method, called the peeled film process, was developed to overcome this serious difficulty (3).

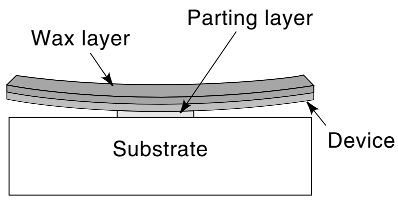

Figure 1. Peeled film geometry with wax layer under tension (not to scale).

The peeled film method involved selectively etching away a thin release layer positioned between the epitaxial film and the substrate upon which it was grown, as described previously, while incorporating a stressed wax layer on the epilayer surface, which caused the epitaxial film to curl upward as the release layer is etched away. This provides a means for the escape and outdiffusion of the reaction products of the etching process from the area between the film and the substrate. This geometry is illustrated in Fig. 1. The wax layer was sprayed onto the substrate and annealed to produce the right amount of tension in the wax (compression in the epilayer) and curvature. Since hydrogen gas has the lowest solubility of any of the reactants or reaction products, the ability to diffuse away the dissolved gas limits the undercutting speed and therefore the permissible hydrofluoric acid concentration. Using this process, large-area films (2″ dia.) have been removed in a relatively short time (<8 h).

This method was demonstrated to be effective for release layers of AlGaAs in which the aluminum content exceeded 50% on GaAs substrates. The quality of the epitaxial layer was unaffected and the resultant substrate was easily reusable with minor cleaning. This same substrate and release layer have been used to produce both solar cells (4) and MESFET devices (5). The general method has also been adapted for other materials (6), as illustrated in Fig. 2, in which the InGaAs layer is the sacrificial release layer. The major constraint on applications of this method is discovering the appropriate highly selective etchant and release layer for the particular required materials.

The third method of producing thin film devices involves the application of a stop-etch layer in between the substrate and the epilayer device and the subsequent dissolution of the complete substrate leaving the thin film device and the stop-etch layer. This method is not as restrictive in terms of material choices as the peeled film method; however, it is time consuming and expensive since the option of reusing the substrate is lost.

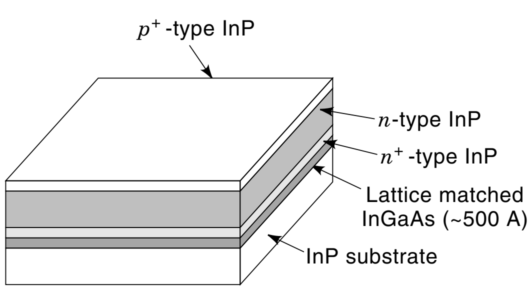

Figure 2. Preferentially etched epitaxial liftoff of indium phosphide solar cell not showing the wax layer (not to scale).

HOST SUBSTRATES

The choice of host substrates depends upon many factors, including the ultimate application for the ELO device and the process used for separation. For some epitaxial liftoff processes, the choice of host substrate must be made before epitaxial liftoff (CLEFT and sacrificial substrate techniques). These techniques provide the ability to support the epilayer(s) during and immediately following liftoff. The peeled film process uses a thin layer of wax to support the epilayer, making the handling of the separated material more difficult, particularly for large areas. The advantage of the peeled film process is that the host substrate is not exposed to the separation process (i.e., chemical etchants, mechanical stresses, etc.); thus, the probability of damage is reduced. In addition, the peeled film process holds a tremendous advantage for applications in which the epitaxial structure must be precisely aligned with features of the host substrate.

Many researchers have used optically transparent substrates (i.e., glass, quartz, etc.) because of the advantage these materials add to their device structure. Several methods of bonding the epitaxial film to the host substrate have been developed for transparent substrates. These methods include transparent adhesives such as Dow Corning DC 93-500, fusion bonding (7), and Van der Waals bonding (8), where intermolecular forces between the two clean surfaces bond the epilayer to the substrate.

Semiconductor wafers are also commonly used as host substrates by many researchers. Several bonding methods have been developed for this set of materials, such as Van der Waals bonding and diffusion bonding under high temperature and pressure where chemical vapor transport fills the space between the substrate and the epilayer (9). Variations of the Van der Waals direct bonding method have been reported. These variations are intended to alter the electrical interface between the host substrate and the ELO film. Yablonovitch (10) reported on a technique for coating a GaAs host substrate with palladium before Van der Waals bonding a peeled film to the substrate. This technique leads to a durable, ohmic bond between the epilayer and the substrate.

The choice of bonding method may be influenced by the postseparation processing sequence desired. It has been demonstrated that a film removed from its original substrate and Van der Waals bonded to a second substrate may have additional epitaxial layers deposited upon it (11). This technique has problems with thermal expansion coefficient mismatch and with blisters caused by trapped contaminates between the ELO film and the substrate, although the regrown epitaxial material has demonstrated promising quality.

APPLICATIONS FOR EPITAXIAL LIFTOFF MATERIALS

Many devices have been demonstrated from ELO materials. The use of ELO materials presents two options for device processing, pre- or postliftoff processing. The choice depends upon many factors, such as alignment requirements, processing compatibility of the host substrate, and so forth. Most devices have been fabricated with a combination of both pre- and postliftoff processing.

One obvious area of applications of ELO materials is in photovoltaics, where the active device only needs to be a few microns thick in the case of III–V materials. Solar cells have been demonstrated by many groups using a variety of ELO techniques (2,4,12–15). These efforts have been driven more from a cost reduction point of view than from any particular operational advantage, given the large area required for most solar arrays. This approach does have several technical advantages, particularly for space applications, where the mass of the array may be significantly reduced through the use of ELO devices.

Other devices that have been demonstrated include:

- AlGaAs/GaAs/AlGaAs diode lasers on glass (16)
- GaAs MESFETs on glass and silicon (5,17)
- InGaAs/GaAs HEMTs (18,19)
- InP/InGaAs photodiode on sapphire (20)
- InGaAs/InP photodetectors (21,22)
- GaAs photodetectors (23–25)
- GaAs LED on silicon (26)
- GaAs MESFET's on InP waveguide structures (27)
- AlGaAs/InGaAs pseudomorphic HEMTs (28)
- AlGaAs/GaAs HBTs (29,30)
- GaAs/AlGaAs multiquantum well photorefractive devices (31)
- AlGaAs/GaAs 2-deg mixer on quartz (32)

One relatively new area of application for epitaxial lift-off materials is as a compliant layer in lattice-mismatched epitaxy (33,34). In this process, a ELO epilayer is bonded to a substrate to form a structure for subsequent lattice-mismatched heteroepitaxial growth. The strain developed due to the lattice-mismatch between the epilayer and the substrate structure is relieved by defect formation in the ELO layer, thereby minimizing the defects in the epilayer. This technique hold promise for a variety of material systems.

This compilation of device applications is by no means exhaustive. Several excellent papers that outline current and potential areas of application are available (35–37).

CONCLUSIONS

Various techniques have evolved to permit device designers additional latitude in optimizing and combining devices using ELO technology. Currently, manufacturing has been limited primarily to the sacrificial substrate ELO technique for small area devices. The widespread demonstration of high-performance ELO devices using other techniques bodes well for future incorporation into manufacturing. The advantages achieved through the application of ELO technology hold tremendous promise for integrated optoelectronic and novel optical devices.

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EQUATIONS. See DATA PRESENTATION.
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EQUIPMENT, FACSIMILE. See FACSIMILE EQUIPMENT.
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ESR. See MAGNETIC RESONANCE.
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