16.9 Epitaxial GaAs lift-off

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A INTRODUCTION

Epitaxial lift-off (ELO) permits the integration of III-V films and devices onto arbitrary material substrates. In this respect, it competes with the lattice mismatched growth of GaAs directly onto silicon which will be reviewed elsewhere in this volume. The main advantages of ELO are: (1) the growth is lattice-matched, producing III-V semiconductor material of uncompromised quality and (2) the substrate choice is flexible.

Historically, there have been various procedures for separating epitaxial films from their growth substrates. As an example of one such successful technology, GaAs photocathodes [1] are made by fusing glass to an epi-wafer and then etching away the entire substrate. Another approach has been to regard the substrate wafer as a kind of re-usable epitaxial growth template. For example Fan [2] has promoted a process in which an epitaxial film is cleaved away from the substrate on which it is grown. Likewise, there have been a number of attempts in the past [3,4] to use selective etching to undercut an epitaxially grown film. ELO falls into this category of thin film separation methods. Recently the problems of etch rate selectivity, bubble formation and thin film handling have been largely overcome [5], permitting rapid progress to be made.

B SELECTIVE ETCHING

ELO relies on the amazingly high etch rate selectivity of $Al_xGa_{1-x}As$ alloys in hydrofluoric acid as the composition changes from x = 40% to x = 100%. Measured selectivities are larger than 100 million to 1. If an ultra-thin AlAs layer (2 nm to 50 nm thick) is the first layer to be grown in a multilayer epitaxial sequence, then a large-area film (up to 2 cm × 4 cm) can be undercut from its growth substrate. The thin film comprising the electronic device is released without the introduction of any foreign layers or substances. The GaAs substrate is left intact and can be re-used if so desired, while the epitaxial thin film can be cemented or 'Van der Waals bonded' by surface tension forces to any arbitrary substrate.

Etch rates are only weakly dependent upon the acid concentration. The lateral undercutting rate of pure AlAs epilayers in a narrow slot progresses at a velocity of 5 microns per minute or 0.3 mm per hour, provided there is no bubble nucleation of the gaseous etching reaction products. This speed appears to be temperature-independent. It is somewhat slower than the fastest etch rates given in TABLE 1, which were measured at a free surface.

C DEVICE EXAMPLES

When using ELO for the production of specific electronic devices the question of 'preprocessing' versus 'post-processing' arises. In 'preprocessing' the devices are fully processed on the original growth substrates and then lifted off as a complete thin film device. In this case ELO is seen as an alternative form of wafer dicing, but allowing thin film integration onto any substrate.

TABLE 1. The etch rate of various $Al_xGa_{1-x}As$ alloys in microns per minute, immersed in hydrofluoric acid of 49% aqueous concentration. The etching is thermally activated at low aluminium mole-fraction, but appears to be diffusion limited at high aluminium mole-fraction. These etch rates should be used only as a general guide since there are significant sample to sample variations.

Aluminium			Acid temperature			Activation energy (eV)
Mole fraction	230 K	250 K	273 K	296 K	328 K	
40%		1.8×10^{-6}	1.2×10^{-5}	5.6×10^{-5}	3.8×10^{-4}	0.5
50%	1.6×10^{-3}	1.2×10^{-2}	7.4×10^{-2}	3.8×10^{-1}	2.5	0.48
64%	1.0	3.2	9.8	15		0.29
80%	6.5	11	18	28		0.13

In 'post-processing', by contrast, an epitaxial film is bonded to a new substrate and only then processed into devices. This has the advantage of permitting easy alignment to existing substrate patterns using conventional lithographic tools. Depending on the specific device application, the choice of processing sequence generally falls somewhere between these two extremes.

At this point a large number of devices have been demonstrated using some combination of pre- and post-processing:

1. Double heterostructure GaAs/AlGaAs thin film diode lasers [6] on glass.

2. GaAs metal-semiconductor field effect transistors (MESFETS) [7] on glass and silicon.

3. Strained single quantum well InGaAs/GaAs high electron mobility transistors [8] (HEMTs).

4. Regrowth of GaAs quantum wells has been demonstrated [9] on GaAs lift-off films, 'Van der Waals bonded' to silicon substrates. Regrowth after ELO is an extreme example of 'post-processing'.

5. A high speed InP/InGaAs photodiode on a sapphire substrate [10]. This is noteworthy because it is the first application of ELO to InP growth substrates. It required the use of an ultra-thin (2 nm) pseudomorphic strained AlAs release layer.

6. Waveguide coupling [11,12] into GaAs thin-film photodetectors lying on $LiNbO_3$ and glass waveguide substrates.

7. GaAs light emitting diodes on metallized silicon substrates [13]. In these post-processed devices, an alloyed electrical contact is made between the thin film GaAs structure and the substrate.

8. GaAs MESFETs have been integrated [14] with InP waveguide structures.

9. Double heterostructure excitonic absorption test structures [15] on glass substrates.

D FILM CURVATURE AND GAS OUT-DIFFUSION

ELO relies upon the escape of the gaseous reaction products of etching. An important role is played by the wax providing mechanical support to the epitaxial film as it lifts off the substrate. Due to the difference in thermal contraction between the wax layer and the GaAs film upon cooling down from the wax annealing temperature, the film becomes curved [5]. This curvature opens up the escape channel for gaseous etching products. The maximum permissible [5] undercutting speed v to allow out-diffusion while preventing bubble nucleation is:

$$v = \frac{Dn}{m\,N\,\pi\,\sqrt{Rt\,/\,2}} \qquad (1)$$

where n is the saturation solubility of the etching reaction products (which may include H_2 or possibly AsH_3), N is the molar concentration of AlAs, D is the gaseous diffusion constant, m is the number of moles of reaction product per mole of AlAs, t is the thickness of the AlAs epilayer and R is the radius of curvature induced by thermal contraction. For H_2 gas in aqueous media, n/N is approximately 2×10^{-5} [16], and D is approximately 5×10^{-5} cm^{-2} /s [17]. The fractional difference in thermal contraction, K, between the wax and GaAs produces the following radius of curvature:

$$R = \frac{T_w^3\,Y_w}{6K\,T_g^2\,Y_g} \qquad (2)$$

where T_w and T_g are the thickness of the wax and GaAs films respectively, and Y_w and Y_g are the Young's moduli of the wax and GaAs films, respectively. EQN (2) is valid when $T_w/T_g >> 1$ and $Y_g/Y_w >> 1$. Typically T_w/T_g is about 100, Y_g/Y_w is about 100 and K is about 0.01 resulting in approximately a 10 cm radius of curvature. This curvature limits the permissible speed of undercutting in EQN (1).

E CONCLUSION

The ability to separate the growth substrate from the active thin film permits a considerable increase in the sophistication of materials engineering. In particular, the properties of the supporting substrate can be optimized separately from those of the epitaxially grown film. There are many attributes in which novel supporting materials would have properties superior to III-V growth substrates, among them being: substrate dielectric constant for increased speed in supercomputers; thermal conductivity for high power applications; cost for solar cell applications; weight for space applications; radiation hardness for military electronics; mechanical strength and mechanical flexibility. Most importantly ELO opens up the prospect for opto-electronic integration (i.e. GaAs films on silicon) and electro-optic integration (i.e. GaAs films on $LiNbO_3$ and glass waveguides). The 'Van der Waals' bonding process [18] employing surface tension forces plays a role in many of these applications.

ELO can be expected to impact many other research and development projects that depend on

the ability to marry thin layers of dissimilar materials. The most important applications are probably yet to be discovered.

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