HIGH-SPEED InP/GaInAs PHOTODIODE ON SAPPHIRE SUBSTRATE

Indexing terms: Optoelectronics, Photodiodes, Epitaxy, Optical communications

Using epitaxial lift-off by selective wet-chemical etching, we have transferred an InP/GaInAs photodiode onto a sapphire substrate. The transferred diode shows an estimated 13·5 GHz bandwidth and 90% internal quantum efficiency. Our technique has promising applications in high-performance optoelectronic circuits for fibre-optic communications systems combining devices from different material systems.

Introduction: The widespread introduction of fibre-optic links in communications systems calls for the integration of high-performance optoelectronic and electronic devices. These devices usually have largely different materials requirements. In many optoelectronics integrated circuits, compromises in the material structures of both families of devices are made to enable integration. These compromises, however, often reduce performance well below the state-of-the-art of hybrid circuits. Attempts have been made to circumvent these problems using, most notably, heteroepitaxy.[1,2] Although these approaches have their merits, the approach presented here provides a more practical solution: the lift-off of epitaxially grown layers and their transfer to a different substrate.[3]

Originally presented for the GaAs material system, it has already been demonstrated that devices like GaAs MESFETs[4] can be successfully transferred to nonsemiconducting substrates like glass, with little or no effect on the device performance. The preparation of thin film lasers on a glass substrate,[5] and the integration of GaAs planar photodetectors with $LiNbO_3$ waveguides[6] demonstrates the ability to combine important material systems for optoelectronics in a quasimonolithic form. Recently, high-performance GaAs quantum-well structures were grown on a lifted-off GaAs layer redeposited on a Si wafer,[7] proving this technique to be a viable alternative to direct GaAs-on-Si heteroepitaxy.

As the focus of interest in fibre-optic communications systems shifts to longer wavelengths, the semiconductor lift-off technique will be of great interest if it can be shown that thin film devices fabricated on different semiconductor substrates like InP and GaAs can be combined on a common substrate and interconnected. In this letter, we report on an important step in this direction. For the first time, a thin film InP/GaInAs device has been lifted off and transferred to a sapphire substrate. Its DC and transient optoelectronic response have been characterised on the new substrate.

Device fabrication: The layer sequence shown in Table 1 was grown by MOCVD. The top three layers are typical for a high-speed single-heterostructure *pin* photodiode. The 1 μm-thick, nonintentionally doped InP layer below serves as support after lift-off. 5 nm of lattice-mismatched AlAs provides the release layer for the wet-chemical etching as described in the following paragraphs. Two buffer layers were grown on the InP substrate to improve the crystal quality. The AlAs release layer was grown at 650°C and all other layers at 625°C.

Next, a pin mesa structure was wet-chemically etched. The structure is similar to that of a high-speed GaInAs/InAlAs *pin* previously reported.[8] AuBe/Au was deposited by e-beam evaporation for the *p*-, and Au/Sn/Au was used for the *n*-contacts. The contact were subsequently alloyed at 400°C for 3 s. At this point, prior to the polyimide passivation and final metallisation, the processing was interrupted and the lift-off was done.

Table 1 LAYER SEQUENCE

0·5 μm GaInAs	$p = 3 \times 10^{18}\,cm^{-3}$
2·0 μm GaInAs	$n = 5 \times 10^{15}\,cm^{-3}$
0·5 μm InP	$n = 2 \times 10^{18}\,cm^{-3}$
1·0 μm InP	Nominally undoped
5 nm AlAs	Release layer
0·5 μm GaInAs	Buffer layer
0·5 μm InP	Buffer layer
InP substrate	

The lift-off processing was begun by painting Apiezon Type-W wax on the wafer, for a total thickness of 100 μm. The wax was subsequently cured. Grinding exposed the edges of the coated wafer to allow the etch solution to attack the release layer. Next, the wafer was placed in 10% hydrofluoric acid, undercutting the AlAS at a rate of approximately 0·3 mm/h. After the top layers were completely separated from the InP substrate, they were transferred to a sapphire substrate while still floating in water. Gentle pressure removed most of the water between the lifted-off semiconductor layers and the sapphire substrate. The samples were then allowed to air dry, permitting the water to diffuse out between the lift-off layer and the sapphire substrate. When dry, the semiconductor layers were 'van der Waals bonded' to the sapphire. The wax was then removed using trichloroethylene.

The processing continued with a spin-on polyimide coating. Windows were opened over the *p*- and *n*-contacts, the polyimide was cured and the final metal (20 nm Ti, 200 nm Au) was structured by lift-off. The polyimide improved the edge coverage and isolates the final metal pads from the bottom InP layer which has a nonnegligible residual conductivity. The final structure can be seen in Fig. 1. The active area of the photodiode is $24 \times 24\,\mu m^2$.

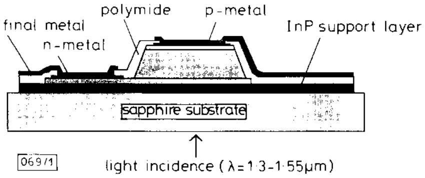

Fig. 1 *Schematic cross-section through fabricated InP/GaInAs photodiode on sapphire substrate*

Experimental results: The diode DC *I/V* characteristics were measured prior to and after lift-off. The dark current at a typical operating bias of −5 V was 0·5–2 μA in both cases. The dark current was not altered by the lift-off procedure. Conventional photodiodes using the same processing, but without the AlAs release layer, had dark currents of < 50 nA. We attribute the increase in dark current to an increase in dislocation density since the thickness of the nonlattice-matched AlAs release layer is larger than the critical thickness. A thinner release layer, less than the critical thickness, is expected to yield results comparable to lattice-matched devices. AlAs layers as thin as 2 nm have been used successfully. As pointed out in Reference 2, a thinner release layer can be beneficial to the lift-off process in general.

The theoretical internal quantum efficiency at 1·3 μm, as determined from the absorption layer thickness, is 90%. This value was experimentally confirmed, within the accuracy limits of our set-up.

To determine the transient optoelectronic response of the device, we used a gain-switched semiconductor laser. A commercial laser diode module (AT&T Astrotek 215) with a fibre-optic pigtail was modulated with current pulses of 350 mA peak and 95 MHz repetition rate. The optical pulsewidth, estimated from measurements using a high-speed (> 20 GHz) *pin* photodiode and a fast sampling oscilloscope, was 28 ps. The light output from the fibre was refocussed using a lens and arrived at the photodiode under test through the sapphire substrate. The maximum average optical power in the plane of the photodiode, but without the sapphire substrate, was measured to be 13·7 μW. Assuming a Gaussian pulse shape, we therefore estimate the optical peak power to be 8·2 mW. An optical attenuator was used to check the pulse response for dependency on the incident optical input power.

For the transient optoelectronic testing, the *pin* photodiode was contacted using a Cascade Microtech probe with a bandwidth of 18 GHz. Fig. 2 shows the pulse response at $4\,mW_{peak}$. The full width at half maximum (FWHM) was 46 ps experimentally, and the rise time of 33 ps is completely set-up limited. We note the symmetrical shape of the pulse response and the absence of a trailing pulse foot which could be attributed to traps or interface effects. The pulsewidth was independent of the incident power ranging down to $8\,\mu W_{peak}$. At the highest incident power, a slight increase of the FWHM to 51 ps was observed. The pulse response of the measurement system (laser and sampling oscilloscope) was previously determined to be 40 ps FWHM. The intrinsic impulse response of the *pin* photodiode under investigation can therefore be estimated to be 23 ps FWHM, with an equivalent bandwidth of 13·5 GHz. This is comparable to previously published photodiodes with identical geometrical structure on lattice-matched layers.[8]

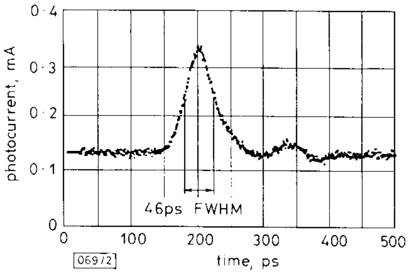

Fig. 2 *Pulse response of pin photodiode after lift-off at 4 mW optical peak power, showing 46 ps FWHM*

Conclusion: We have successfully demonstrated the transfer of a high-speed *pin* photodiode for 1·3 μm/1·55 μm fibre-optic communications to a sapphire substrate using the epitaxial lift-off technique. Preprocessed *pin* photodiodes were lifted off, transferred, and a final metallisation applied, proving that an interconnection with other devices from different material systems can be made with a final metal mask and standard photolithographic techniques. Although the dark current was still relatively high, possibly due to the lattice-mismatched release layer, the electrical and optoelectronic performance did not deteriorate because of the lift-off.

A detector bandwidth of 13·5 GHz and a quantum efficiency of 90% give excellent prospects for the realisation of a high-performance high reliability fibre-optic receiver combining an InP/GaInAs photodiode with well established GaAs electronics. Using a lithographically defined final metal instead of bonding will improve the yield and keep wiring parasitics within close tolerances. As sapphire is an excellent microwave substrate, interstage matching elements[9] can easily be incorporated.

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NEW $\lambda/4$ PHASE-SHIFT METHOD BY CONVERSION OF REFRACTIVE INDEX DIFFERENCE AND APPLICATION FOR 1·5 μm GaInAsP/InP DFB LASER

Indexing terms: Semiconductor lasers, Lithography

A new method to introduce a phase shift of $\pi/2$ equivalently by inversion of the refractive index difference, which can be easily done by conventional photolithography, is proposed and applied for a 1·5 μm GaInAsP/InP DFB laser. The $\lambda/4$-shifted effect was confirmed by observing the lasing spectrum of an antireflection-coated DFB laser below threshold under CW operation.

Introduction: Dynamic-single-mode (DSM) semiconductor lasers, such as distributed Bragg reflector (DBR), distributed feedback (DFB) and distributed reflector (DR)[1,2] lasers are very attractive light sources for high-bit-rate optical communication. In these lasers consisting of corrugated waveguides, it is important to adjust the lasing wavelength to the Bragg wavelength for stable single-mode operation. Theoretically, it was pointed out that an additional phase shift of $\pi/2$ in the central area between both sides of active or passive reflectors must be introduced for the Bragg wavelength oscillation.[3,4] Various methods to form an additional phase shift of $\pi/2$ have been reported, such as electron beam lithography,[5] nonuniform stripe width,[6] a phase coupling waveguide[7] and simultaneous holographic exposure of positive and negative photoresists.[8,9]

In this letter we propose and experimentally verify a new $\pi/2$ phase shift method by inversion of the refractive index difference, which can be easily fabricated by conventional photolithography.

Method: We first explain the principle of a π shift in the equivalent refractive index by inversion of the refractive index difference. Fig. 1 shows schematic diagrams of (*a*) the corrugation profile, (*b*) the equivalent refractive index profile and (*c*) the waveguide structure to realise a π shift of the equivalent refractive index. Corrugations are formed on the layers with different refractive index n_1 and n_3 ($n_1 > n_3$) by conventional holographic lithography without any actual phase change in the grating, and another layer with refractive index n_2, which is between n_1 and n_3 ($n_1 > n_2 > n_3$), is grown over the entire surface. In region I the variation in equivalent refractive index coincides with that of the actual grating because the refractive index n_1 is larger than n_2, whereas the variation in the equivalent refractive index in region II is inverted from that of the actual grating because n_1 is smaller than n_2. Consequently we can introduce a $\pi/2$ phase shift (π shift of equivalent refractive index) at the boundary of regions I and II.

Experiments: This new method was applied to fabricate a $\lambda/4$ phase-shifted DFB laser as shown in Fig. 2. The fabrication