all but the larger area devices or those with significantly submicrometer finger spacings, is limited by carrier transit times rather than the *RC* charging time. We present the results of 2*D* calculations of the transit time limited impulse response of the detector for 1.3- and 1.5-μm incident radiation, and obtain excellent agreement with the experimental results. We then expand the calculations and show how the bandwidth of the generic InGaAs device varies with finger spacing, applied bias, thickness of the absorption layer, and incident wavelength. These simulations enable the design of InGaAs M-S-M detectors for optimum combination of bandwidth and quantum efficiency.

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VIA-2 Long-Wavelength (1.0–1.6 μm) $\mathrm{In_{0.53}[Ga_xAl_{1-x}]_{0.47}As/In_{0.53}Ga_{0.47}As}$ MSM Photodiode—H. T. Griem, S. Ray, J. L. Freeman, and D. L. West, Boeing Electronics High Technology Center, P.O. Box 24969, M/S 7J-56, Seattle, WA 98124-6269, and W. J. Schaff, School of Electrical Engineering, Phillips Hall, Cornell University, Ithaca, NY 14853.

We report a novel metal-semiconductor-metal (MSM) Schottky photodiode using a nominally lattice-matched $\mathrm{In_{0.53}[Ga_xAl_{1-x}]_{0.47}As}$ (graded)/$\mathrm{In_{0.53}Ga_{0.47}As}$ structure grown by MBE on a semi-insulating InP substrate. Previously, MSM photodiodes in the 1.0–1.6 μm wavelength range suffered from low Schottky-barrier heights (~0.2 V) on InGaAs, leading to excessive dark currents [1]. In recent months, low dark current MSM's on InGaAs have been demonstrated by using either a strained GaAs/InGaAs superlattice [2] or a lattice-matched InAlAs/InGaAs superlattice [3] to enhance the Schottky-barrier height. Our approach to barrier enhancement uses a lattice-matched compositionally graded InGaAlAs capping layer. This lattice-matched layer does not suffer from the nonradiative recombination centers which may result from strained/relaxed layers or superlattice interfaces associated with previous work. Abrupt band-edge discontinuities, which inhibit the collection of photogenerated carriers, are also eliminated. The structure consists of an $\mathrm{In_{0.53}Ga_{0.47}As}$ absorbing layer 1 μm thick beneath 1 μm of $\mathrm{In_{0.53}[Ga_xAl_{1-x}]_{0.47}As}$ linearly graded between $x = 1$ and $x = 0$. Finger width and spacing were both 1.0 μm with a 50×50 μm device active area.

A detector responsivity of 0.35 A/W was measured at 1.3 μm with a 10-V applied bias; the corresponding internal quantum efficiency is in excess of 90 percent. The associated dark currents are very low: 35 nA at 10 V and 500 nA at 20 V. Detector capacitance was 70 fF. Preliminary high-speed measurements with a gain-switched 1.3-μm laser diode show an instrumentation-limited impulse response of 55 ps.

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VIA-3 High-Speed InP/InGaAs Photodiode on Sapphire Substrate Prepared by Epitaxial Lift-Off—H. Schumacher, T. J. Gmitter, H. P. LeBlanc, R. Bhat, E. Yablonovitch, and M. A. Koza, Bellcore, 331 Newman Springs Rd., Red Bank, NJ 07701.

The widespread introduction of fiber-optic communications systems calls for the integration of high-performance electronic and optoelectronic devices. While research on selective area and hetero-epitaxy necessary to solve the conflicting materials requirements continues, a lift-off technique for epitaxial layers with subsequent deposition on a different substrate [1] may be a more near-term solution. Originally demonstrated for the GaAs material system, we have, for the first time, applied this technique to InP/InGaAs devices, demonstrating the ability to combine long-wavelength optoelectronic devices with electronic components from different material systems, e.g., GaAs. Furthermore, we have shown that a passivation layer and an interconnecting final metal layer can be applied to the devices after lift-off on the new host substrate.

The layer sequence for the lift-off process was grown by OMCVD. Underneath a conventional single-heterostructure p-i-n layer sequence (0.5-μm InGaAs, $p = 5 \times 10^{17}$ cm^{-3}, 2-μm InGaAs, not intentionally doped, 0.5-μm InP, $n = 10^{18}$ cm^{-3}) an additional 1-μm-thick not intenionally doped InP layer was included to support the device structure after lift-off. Below this layer came the AlAs release layer (5 nm thick), and not intentionally doped InGaAs and InP buffer layers. The p-i-n photodiode had an active area of (24×24) μm^2 [2]. After two wet-chemical mesa etches, p- and n-contacts were structured and alloyed. At this point, the standard pin device processing was interupted for the lift-off procedure.

The wafer was paint-coated with Apiezon Type *W* wax, the wax was subsequently cured at 160°C for 30 min. The wax was removed around the edges of the wafer by grinding, exposing the semiconductor layers. Next, the wafer was placed in 10 percent hydrofluoric acid diluted in water at 0°C. Diluted hydrofluoric acid was shown to attack only the AlAs release layer with very high $((>10^7)$ selectivity. The release layer is undercut about 0.3 mm/min. After the top layers were completely separated from the InP substrate they were transferred to the sapphire substrate while still floating in water. Gentle pressure removed most of the water between the lifted-off layers and the substrate. The samples were then allowed to air dry. When dry, the semiconductor layers are "van der Waals bonded" to the substrate. The wax is removed using trichloroethylene.

In the final steps, the wafer is passivated with a polyimide film and the final metal is structured. The devices were tested on wafer using a Cascade Microtech probes with 18-GHz bandwidth. A gain-switched laser diode ($\lambda = 1.3$ μm, 27-ps FWHM for the emitted pulse) and a sampling oscilloscope were used for optoelectronic time-domain testing. The pulse response had a full width at half maximum of 46 ps. With a system impulse response for the laser pulse and oscilloscope combined of 40 ps (FWHM), this leads to an estimated bandwidth of 13.5 GHz. The quantum efficiency was 90 percent, the dark current typically 0.5 μA. No detrimental effects were seen due to the lift-off process. The dark current can be explained by stress-induced dislocations due to the non-lattice-matched AlAs release layer.

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VIA-4 Ionization Thresholds in Silicon and Germanium Avalanche Photodiodes Under Hydrostatic Pressure and Strain—J. Allam, I. K. Czajkowski, M. Silver and A. R. Adams, Department of Physics, University of Surrey, Guildford GU2 5XH, UK, and M. A. Gell, British Telecom Research Labs., Martlesham Heath, Ipswich IP5 7RE, UK.

Silicon has the lowest multiplication noise of any known semiconductor for avalanche photodiodes (APD's), due to the large ra-