contain high densities of threading dislocations.

In conclusion, by using a thermally cycled GaAs defect-filtering layer to improve the quality of the laser structure, we have achieved room-temperature cw operation of GRIN-SCH GaAs/AlGaAs diode lasers grown on Si entirely by OMVPE. However, major improvements in material quality are still necessary in order to increase the reliability of these devices to the level required for practical applications.

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Performance characteristics of $In_{0.6}Ga_{0.4}As/In_{0.52}Al_{0.48}As$ modulation-doped field-effect transistor monolithically integrated with $In_{0.53}Ga_{0.47}As$ *p-i-n* photodiodes

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Pseudomorphic $In_{0.6}Ga_{0.4}As/In_{0.52}Al_{0.48}As$ 1 μm gate modulation-doped field-effect transistors have been monolithically integrated with $In_{0.53}Ga_{0.47}As$ photodiodes for front-end photoreceivers using one-step molecular-beam epitaxy and lithography techniques. A 1-μm thick undoped $In_{0.52}Al_{0.48}As$ layer is used to isolate the two devices. The transistors are characterized by g_m (ext) $= 500$ mS/mm and $f_T = 9$ GHz. The temporal response of the photodiodes is characterized by a linewidth of 60 ps. The eye pattern of the photoreceiver circuit for 1.7 Gbit/s pseudorandom optical signal is open and it is expected that the circuit can perform at bandwidths up to 2.5 GHz. Measured bandwidths of $\sim$6.5 GHz are obtained by using regrowth.

There is increasing interest and activity in the area of monolithic optoelectronic integration and in optoelectronic integrated circuits (OEIC).[1-5] Technological issues related to successful monolithic integration of high-performance devices depends on the basic schemes of integration. There are two choices: a vertical scheme which is easier to implement by epitaxy, but may be limited by parasitic capacitances of the isolating layer, and a planar scheme which can either involve regrowth and/or diffusion or use devices such as junction field-effect transistors and metal-semiconductor-metal photodiodes.

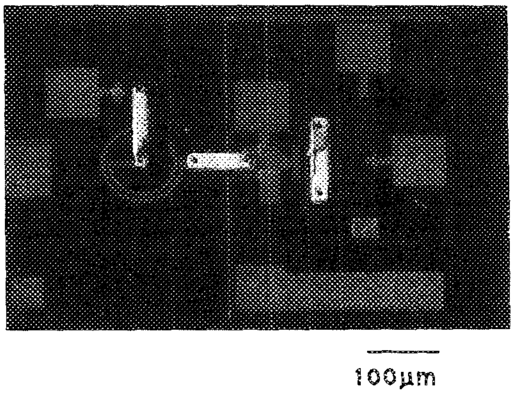
We report here the performance characteristics of an integrated *p-i-n* photodiode/modulation-doped field-effect transistor (MODFET). A pseudomorphic $In_{0.6}Ga_{0.4}As/In_{0.52}Al_{0.48}As$ MODFET and $In_{0.53}Ga_{0.47}As$ *p-i-n* have been integrated using the vertical scheme. Pseudomorphic MODFETs have recently demonstrated very impressive low-noise performance[6] and the *p-i-n* photodiode is also a low-noise device. Furthermore, in the design of the circuit we have included a monolithic integrated inductor to improve the high frequency response. The inductor values were estimated from a frequency response analysis of the equivalent circuit of the photoreceiver.[7] The best response characteristics were achieved for $L = 0.5$ nH.

The photoreceiver structure, schematically shown in Fig. 1(a), was grown on (001) semi-insulating InP by molecular-beam epitaxy. The integrated *p-i-n* MODFETs were made by a ten level process which includes several etching steps to contact the MODFET InGaAs doping layer, n^+ and p^+ layers of the *p-i-n* diode, and isolate the devices. Air-bridge technology was used for interconnection between dual sources and other elements shown in Fig. 1(b). The MODFETs have 3.5-μm source drain separation and gate dimensions of $1 \times 100\,\mu$m. The photodiodes are $30 \times 50\,\mu\text{m}^2$ in area and exhibit leakage currents less than 1 nA at a reverse bias of 5 V at room temperature.

The measured dc current-voltage characteristics of isolated 1-μm gate MODFETs show depletion mode behavior and good pinchoff. The maximum extrinsic transconductance is 500 mS/mm as shown in Fig. 2(a). The microwave performance of the MODFETs were determined from measured S-parameters in the frequency range 45 MHz–18 GHz using a CASCADE wafer probing station. The cutoff frequency of the transistor has been evaluated by plotting the current gain (h_{21}) as a function of frequency [Fig. 2(b)] and is found to be 9 GHz. This result corresponds to the extrinsic performance of the device.

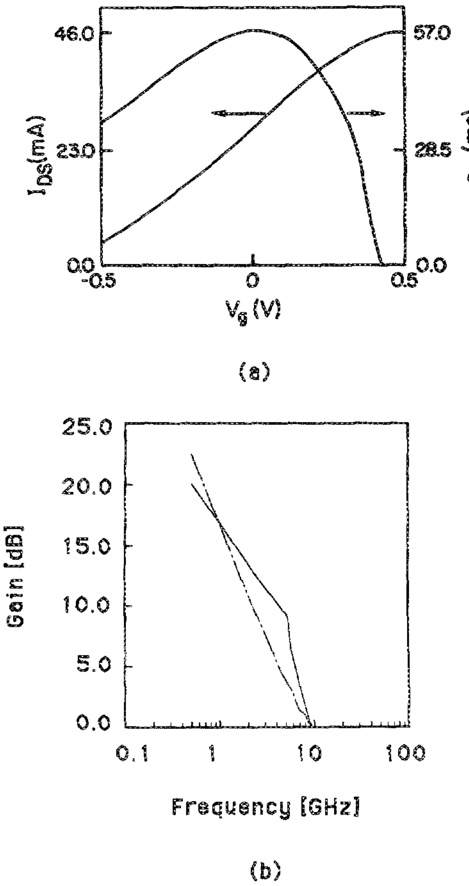
300Å	n+	InGaAs	3×10^{18} cm^{-3}
200Å	i	InAlAs	
40Å	n+	InAlAs	5×10^{18}
30Å	i	InAlAs	
150Å	i	$In_{0.6}Ga_{0.4}As$	
400Å	i	InGaAs	
10Å/10Å	i	InGaAs/InAlAs S.L.	20 periods
1 μm	i	InAlAs	
1000Å	n+	InGaAs	3×10^{18}
3000Å	n+	InAlAs	3×10^{18}
7500Å	i	InGaAs	
100 Å	i	InAlAs	
5000Å	p+	InGaAs	2×10^{18}
5000Å	p+	InAlAs	2×10^{18}
		S.I. InP Substrate	

(a)



(b)

FIG. 1. (a) Schematics of the fabricated *p-i-n* MODFET; (b) SEM photomicrograph of integrated device with air bridges.



(a)

(b)

FIG. 2. (a) Measured dc characteristics and (b) high frequency current gain of an isolated 1-μm gate MODFET.

The response speeds of the unconnected photodiodes and the *p-i-n* MODFET circuit were measured with an AlGaAs pulsed diode laser ($\lambda = 850$ nm) having a nominal pulse width of 100 ps. The photodiodes were mounted on a coplanar stripline and dc bias was provided through a HP 11612A bias-T network. The *p-i-n* MODFET was also similarly mounted for the response speed measurements. The microwave output resulting from pulsed photoexcitation was taken out from the drain or the source terminal through a second bias-T network. Best performance is observed with the output signal from the source. The responsivity of the unconnected photodiode at ~4 V bias is ~0.65 A/W and the impulse response is characterized by a full width at half maximum (FWHM) of 60 ps. The microwave output pulse response to 100 ps laser excitation with the photodiode biased at 4 V is shown in Fig. 3. The rise time is limited by the laser pulse rise time, which is ~150 ps. The FWHM is ~400 ps, which translates to a bandwidth of ~2 GHz. The measured eye pattern for 17 Gbit/s pseudorandom NRZ optical signals is shown in Fig. 4.

In the course of our measurements we have observed that distributed capacitive effects,[1] mainly resulting from the undoped InAlAs isolating layer, are responsible for degrading the microwave performance of the FETs and per-

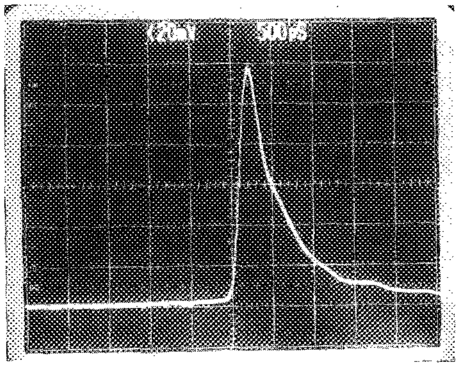


FIG. 3. Measured temporal response characteristics of integrated *p-i-n* MODFET to 100 ps AlGaAs laser pulse excitation.

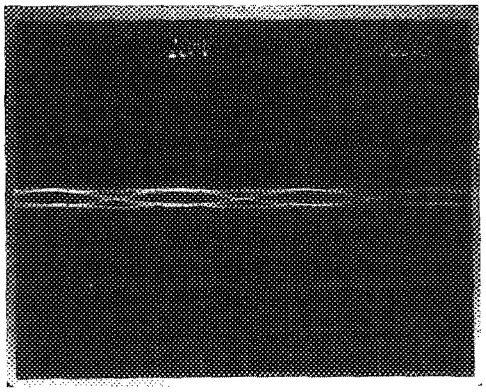


FIG. 4. Measured eye pattern for 1.7 Gbit/s pseudorandom NRZ optical signal.

haps the bandwidth of the circuit. We have performed a SPICE simulation of the photoreceiver[8] taking into account an equivalent circuit resulting from the measured S parameters and the additional parasitic capacitances due to the InAlAs layer. The calculated 3-dB cutoff frequency was found to be 2.1 GHz, which is in good agreement with the measured values. The highest bandwidth measured recently in an InP-based OEIC optoelectronic receiver was a few hundred Mbit/sec.[9] In this receiver an InGaAs junction FET is integrated with an InGaAs *p-i-n* photodiode. Higher bandwidths of 5–7 GHz have been achieved with GaAs-based submicron devices.[2,3] The merits of our integration scheme lie in one-step epitaxy and the possibility of low noise performance with optimized circuit design. We are investigating the possibility of selectively implanting and disordering regions below the active MODFET device so as to eliminate the distributed capacitance problem. With that, the simple circuit demonstrated here could very easily achieve bandwidths ~10–15 GHz. The other alternative is to use regrowth. We have fabricated and characterized a preliminary InP-based photoreceiver circuit where an as-grown *p-i-n* diode with a 1 μm *i*-region has been integrated with a 1-μm gate pseudomorphic InGaAs/InAlAs MODFET. The as-grown MODFETs have $g_m = 380$ mS/mm and $f_T = 30$ GHz. The *p-i-n* diodes have a very low dark current of 30 nA at -10 V. From the temporal response characteristics of the circuit a bandwidth of 6.5 GHz is obtained, which is perhaps the highest value for an InP-based photoreceiver. Optimization of the circuit design is being made to produce bandwidths $\geqslant 10$ GHz.

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