InGaAsP *p-i-n* photodiodes for optical communication at the 1.3-μm wavelength

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The preparation and properties of Cd-diffused *p-n* homojunction InGaAsP photodiodes designed specifically for operation at the 1.3-μm wavelength are described. At a reverse bias of 10 V, the dark current of these diodes was as low as 15 pA. The peak responsivity at 1.3-μm wavelength was 0.7 A/W. An impulse response (full width at half maximum) of 60 ps and a 3-dB bandwidth of 5.5 GHz were achieved.

The development of optical fibers with low loss and low dispersion at the wavelengths around 1.3 and 1.55 μm has spurred extensive research in near-infrared lasers and detectors for application to optical communication systems in these spectral regions.[1] In addition to the development of 1.65-μm $In_{0.53}Ga_{0.47}As$ photodiodes,[2,3] a considerable effort has been devoted to the fabrication of low dark-current photodiodes using $In_{1-x}Ga_xAs_yP_{1-y}$ for detecting laser signals in the wavelength region around 1.3 μm.[4-6] However, the band gaps of low dark-current and high-efficiency InGaAsP photodiodes reported to date have corresponded to a 1.3-μm wavelength or less. The energy gap, hence the absorption edge, of the InGaAsP active layer in these photo diodes was very close to that of the 1.3 μm lasers used to characterize them since a similar material composition was used for both. The resulting penetration depth of $\lambda = 1.3$-μm laser radiation in the 1.3-μm InGaAsP layer of these photodiodes is more than 2 μm.[7,8] As a result, with an optical signal of 1.3-μm wavelength the responsivity of the photodiode is lower, and the temporal response is degraded because of the large absorption distance. In this paper we describe the fabrication and properties of some experimental InGaAsP homojunction photodiodes with a 1.37-μm band gap for use in the wavelength region around 1.3 μm. The dark current was as low as 15 pA at a reverse bias of 10 V. The responsivity, without antireflection coating, was about 0.7 A/W at 1.3-μm wavelength. An impulse response (full width at half maximum) of 60 ps and a 3-dB bandwidth of 5.5 GHz was achieved with a mesa size of $100 \times 70\ \mu m^2$.

By compositional adjustment of the band gap, InGaAsP photodiodes can be optimized for use at a specific wavelength by using the maximum band gap which still has a high enough absorption coefficient to yield high efficiency and fast temporal response at the desired wavelength. The large band gap minimizes the thermally generated dark current which increases with decreasing bandgap. The $In_{0.73}Ga_{0.27}As_{0.66}P_{0.34}$ quaternary material investigated in our studies yielded low dark-current and high-efficiency photodiodes at the wavelength of 1.3 μm.

The quaternary layers were grown on Sn-doped n^+-InP (100) substrates by liquid-phase-epitaxy (LPB) techniques. Prebaked In melt with added weighed amounts of GaAs, InAs, and InP were loaded into the appropriate wells of a high-purity graphite boat. All of the solution components were baked out in hydrogen. After bakeout, the reactor was cooled to the saturation temperature, 650 °C, at which point an undoped InP wafer was pushed under the quaternary melt and held for 1 h at the saturation temperature to ensure phosphorus saturation in the quaternary melt. This baking procedure was effective in lowering the background net donor concentration. An n^+-InP substrate and Sn for an n^+-InP buffer layer were then loaded. The temperature of the reactor with flowing H_2 ambient was raised to 670 °C, kept at this temperature for 1 h, and then cooled to 655 °C at which point growth of the InP:Sn buffer layer was started. Just prior to epitaxial growth the substrate was passed under pure In melt for a slight melt back of its top surface. The n^--InGaAsP layer was grown for 5 min, starting at 645 °C, with a resulting thickness of about 3–5 μm.

The top p^+ layer was obtained by Cd diffusion in an evacuated fused silica ampoule, using CdP_2 as a source and InAs powder to obtain arsenic partial pressure. The ampoule was heated to 600 °C for 25 min, and the resulting p^+-n junction depth was about 1 μm. Conventional photolithography and chemical etching were used to define the mesa structure with dimensions of approximately $70 \times 100\ \mu m^2$, which allows for a bond pad 50 μm in diameter. The resulting structure is illustrated in Fig. 1.

Figure 2(a) shows the photoluminescence spectra from the as-grown InGaAsP layer at 300 and 77 K. The band gap of the quaternary layer determined from photoluminescence measurements corresponded approximately to a wavelength of 1.37 μm. The spectral response calibrated with a standard Ge photodiode, of the short-circuit photocurrent of the InGaAsP *p-i-n* photodiode biased at -10 V, is shown in Fig. 2(b). The highest responsivity at the wavelength 1.3 μm was

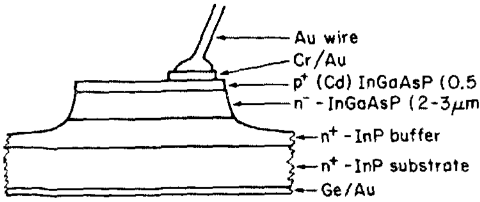

FIG. 1. Schematic cross section of mesa *p-i-n* InGaAsP photodiode.

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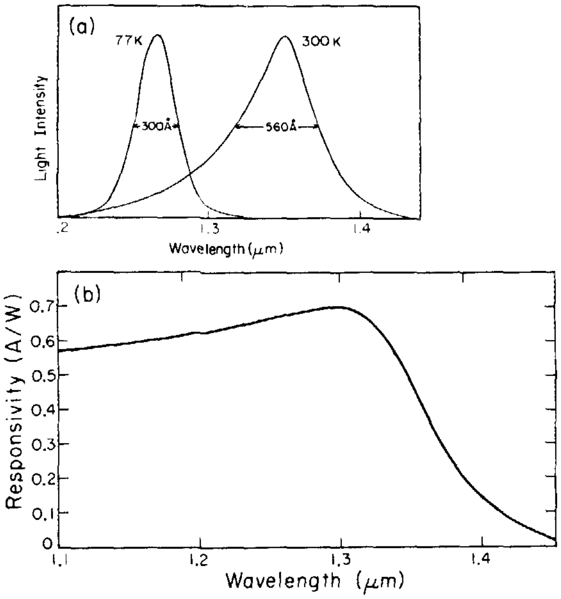

FIG. 2. (a) Photoluminescence spectra from an as-grown InGaAsP layer at 300 and 77 K. (b) Spectral responsivity of a typical InGaAsP *p-i-n* photodiode described in this work.

about 0.7 A/W. The responsivity R increases monotonically with wavelength λ from 1.1 to 1.3 μm, approximately consistent with $R = q\,\eta_e \lambda / hc$, where q is the electron charge, h is Planck's constant, and c is the velocity of light. The external quantum efficiency of this photodiode is about 66%.

The net donor concentration in the n^--InGaAsP layer was determined to be 2–3×10^{15} cm^{-3} from the junction capacitance-voltage measurements. The junction capacitance of a typical diode was 1 pF at zero bias, and it decreased to 0.3 pF at -20 V. The variation of dark current with reverse bias voltage is shown in Fig. 3. The dark current of this diode varies from 5 pA to 0.1 nA as the reverse voltage increases from 5 to 20 V,and thereafter the dark current increased more rapidly until breakdown occurred near -90 V. This increase in the leakage current was due to field emission through the interface states in the depletion region because the n^--InGaAsP layer was completely depleted at a voltage of about -20 V.

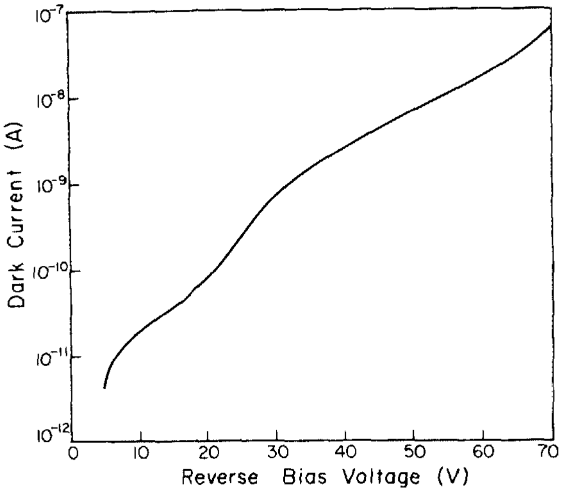

FIG. 3. Dark current vs reverse bias voltage characteristics of a typical InGaAsP *p-i-n* photodiode.

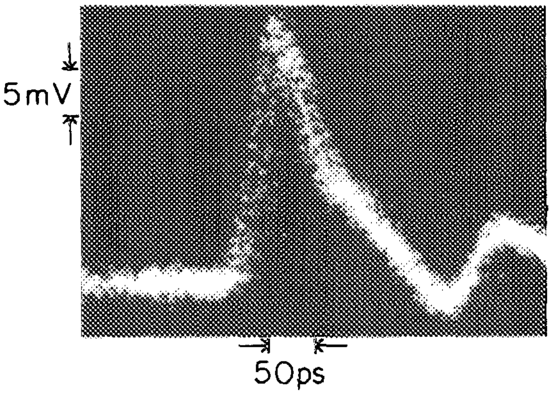

FIG. 4. Pulse response for low-capacitance photodiode biased at a reverse voltage of 20 V.

The temporal response of this photodiode structure was tested by several means. A mode-locked dye laser emitting 4-ps pulses ($\lambda = 5900$ Å) at a 100-MHz repetition rate was used as a signal source. The response of the photodiode to the optical pulse train was observed in the time domain on a sampling oscilloscope having a rise time of 25 ps. Figure 4 shows the impulse response of the photodiode at a 20-V reverse bias. The full width at half maximum was 60 ps.

The photodiode was also tested by measuring its frequency response with a 1.3-μm InGaAsP laser diode which had a 15-mA threshold current and a 10-GHz, 3-dB bandwidth for high-frequency direct-current modulation.[9] The measurement was performed with a sweep oscillator (HP 8350) used in conjunction with a network analyzer (HP 8410 series) and a microwave S-parameter test set (HP 8746B). The microwave measurement yields the scattering matrix coefficient $S_{21} = -KA_{\rm mod}\,T_{\rm ph}$, where K is the coupling factor, $A_{\rm mod}$ is the modulation response of the laser, and $T_{\rm ph}$ is the frequency response of the photodiode. Figure 5 shows the normalized frequency response of the photodiode. The 3-dB bandwidth of the photodiode is 5.5 GHz.

In conclusion, we have fabricated band-gap optimized InGaAsP *p-i-n* photodiodes with low dark current and high responsivity. The rise time and fullwidth at half maximum of the impulse response are 30 and 60 ps, respectively, for a diode with a $100\times 70\,\mu$m^2 photoactive area and at 20-V reverse bias. The 5.5-GHz, 3-dB bandwidth at 1.3 μm was also obtained under the same conditions.

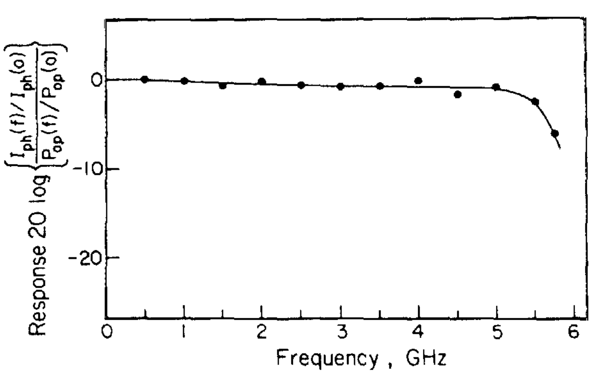

FIG. 5. Frequency response of the photodiode at 20-V bias.

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