High-speed GaAlAs/GaAs *p-i-n* photodiode on a semi-insulating GaAs substrate

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A high-speed, high-responsivity GaAlAs/GaAs *p-i-n* photodiode has been fabricated on a GaAs semi-insulating substrate. The 75-μm-diam photodiode has a 3-dB bandwidth of 2.5 GHz and responsivity of 0.45 A/W at 8400 Å (external quantum efficiency of 65%). The diode is suitable for monolithic integration with other optoelectronic devices.

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One of the main advantages which integrated optoelectronic circuits (IOEC's)[1] have over discrete circuits is the ability to achieve high-frequency modulation due to a significant reduction in parasitic reactances. This is due to the elimination of bond wire connections which have high inductances and to the use of semi-insulating substrates which reduces the parasitic capacitances of bonding pads. While the active electronic devices incorporated in such circuits, e.g., GaAs metal-semiconductor field-effect transistors (MESFET) can be modulated at frequencies exceeding 30 GHz,[2] the overall modulation bandwidth of the integrated optoelectronic circuit is limited, in general, by the frequency response of the light source (i.e., laser) and the photodetector.

Most of the work to date in developing high-speed photodetectors has been done on conductive substrates, and only a few reports have been published on photodetectors fabricated on GaAs semi-insulating substrates which are suitable for monolithic integration with other optoelectronic devices. Among these are the OPFET[3] and the interdigitated photoconductor[4] with response times [full width at half-maximum (FWHM)] of 73 and 80 ps, respectively. In this letter we report on the fabrication of *p-i-n* detector on a GaAs semi-insulating substrate with a response time (FWHM) of 80 ps and rise and fall times of 50 and 65 ps, respectively. This detector was designed to be compatible for integration with GaAs MESFET's and injection lasers fabricated on semi-insulating substrates.

A schematic structure of the detector is shown in Fig. 1. This detector consists of a mesa-type three-layer heterostructure grown by liquid phase epitaxy on a Cr-doped GaAs semi-insulating substrate. The compositions of the layers are n^+-GaAs (Sn doped, $\sim 10^{18}$ cm^{-3}, 2 μm), n^--GaAs (Sn doped, $\sim 2\times 10^{16}$ cm^{-3}, 1.5 μm), and p-Ga$_{0.8}$Al$_{0.2}$As (Ge doped, $\sim 10^{18}$ cm^{-3}, 0.5 μm). The *p*-GaAlAs layer serves as the *p* side of the heterojunction and as a transparent window to the incident light due to its band gap being larger than that of the absorbing n^--GaAs layer. The photodiode is fabricated by etching a 75-μm circular mesa down to the n^+-GaAs layer, and depositing a 2400-Å-thick layer of SiO$_2$. A ring-shaped *p* contact is formed by diffusing Zn through an anular opening in the SiO$_2$, evaporating Cr and Au, and etching the metal. The area of the photodetector not covered by metal has a diameter of 50 μm. The metal bonding pad is deposited on the semi-insulating substrate in order to minimize the parasitic capacitance. The AuGe/Au *n* contact to the n^+-GaAs layer is formed by lift-off and alloying. A photograph of the complete device is shown in Fig. 2.

The leakage current of the diode is 100 pA at a reverse bias voltage of 10 V, corresponding to a leakage current density of $\sim 2\times 10^{-6}$ A/cm^2. At a reverse bias voltage of 20 V, the leakage current is about twice this number. The responsivity of the detector at 8400 Å is 0.45 A/W, which corresponds to an external quantum efficiency of ~65%.

The high-speed response of the photodiode was mea-

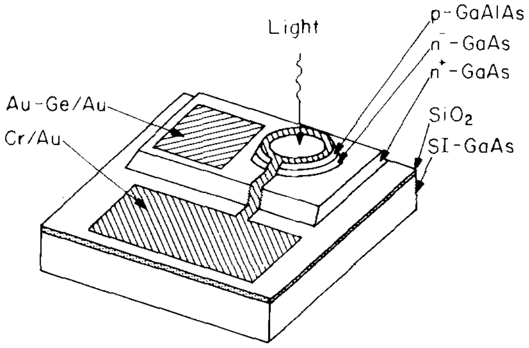

FIG. 1. Schematic diagram of the photodiode.

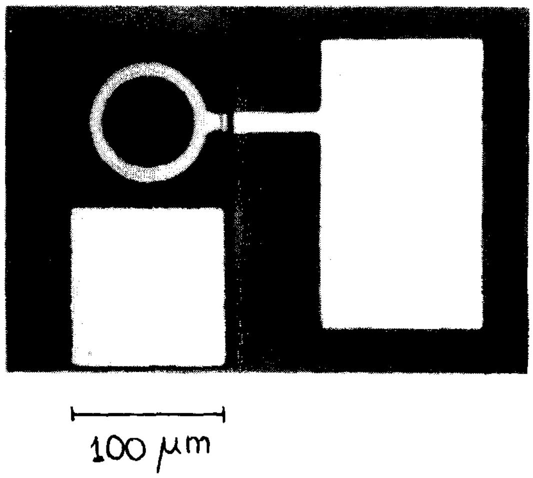

FIG. 2. Photomicrograph of the photodiode.

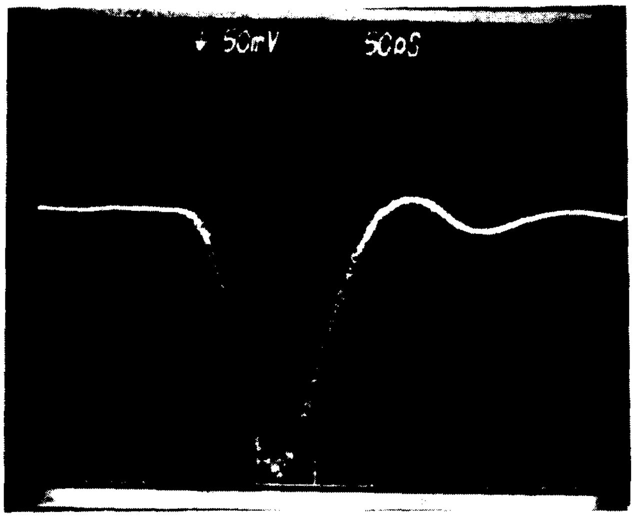

FIG. 3. Impulse response of the photodiode at 15-V bias, as observed on a sampling oscilloscope.

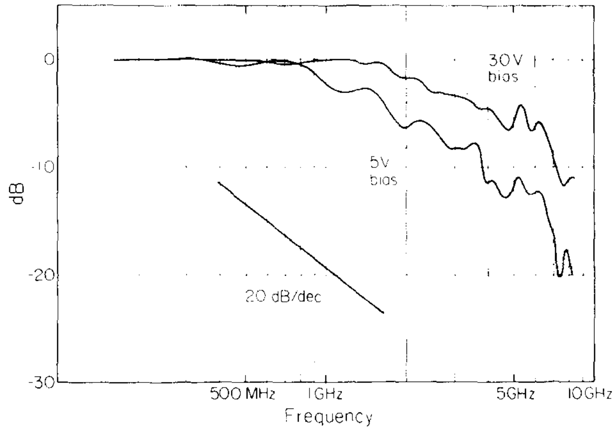

FIG. 4. Frequency response of the photodiode at two bias voltages.

sured using a pulse-excited GaAlAs laser. The photodiode was mounted on 50-Ω microstripline package. The impedance of the package and bond wire was characterized up to 8.5 GHz using a microwave s-parameter test set (hp8746 and 8410 series). It was determined that the package does not significantly effect the photodiode response up to at least 5 GHz. The optical source used was a GaAlAs buried heterostructure laser, driven without a dc bias by a step recovery diode (hp33002) operating at a repetition rate of 100 MHz. A clean train of optical pulses at the same repetition rate of 100 MHz was obtained. The width of the optical pulses was determined by second harmonic generation autocorrelation techniques to be 25-ps FWHM (Gaussian pulse shape assumed). The response of the photodiode to the optical pulse train was observed in the time domain on a sampling scope having a rise time of 25 ps, and in the frequency domain on a microwave spectrum analyser (hp8565A). Figure 3 shows the response of the photodiode at 15-V bias, as observed on the sampling scope. The rise and fall times (10%–90%) were approximately 50 and 65 ps, respectively, and the FWHM was ~80 ps. Observing the photodiode response directly on the microwave spectrum analyser gives a more accurate measurement of the photodiode bandwidth, since the response is not affected by the finite rise time of the sampling scope. The measured frequency response is then deconvolved by the finite width of the optical pulse. Figure 4 shows the frequency response of the photodiode obtained in this manner for two different bias voltages, 5 V and 30 V. Substantial improvement in response speed is obtained as the bias voltage is increased from 0 to 15 V, and no further improvement is realized from a further increase of the voltage. This indicates that the depletion layer has fully occupied the *i* region at ≅15 V, and no reduction in capacitance is possible with further increase in reverse-bias voltage. The capacitance of the device, as determined from the S_{11} reflection coefficient, was ≅0.9 pF. Taking into account the area of the junction, the capacitance per unit area is 0.2 fF/μm^2, comparable to other devices reported.[5] The 3-dB bandwidth of this device, as determined from Fig. 4, is ≅2.5 GHz. The rate of drop off beyond the cutoff is approximately 20 dB/decade, indicating that the response is that of a simple *RC* network due to the diode, and that other parasitic reactances associated with the package do not contribute to the response up to at least 5 GHz.

In conclusion, we have fabricated a *p-i-n* GaAlAs/GaAs photodiode on a semi-insulating substrate. The use of a semi-insulating substrate makes this device suitable for monolithic integration with other optoelectronic devices. The 3-dB bandwidth of this device is 2.5 GHz. We estimate that reduction of the diode diameter to ~25 μm would lead to a bandwidth of 20 GHz.

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