Raman gain constant comprised between $1{\cdot}8 \times 10^{-13}$ and $2{\cdot}7 \times 10^{-3}$ m/W.

This quite large value, as compared to the usually reported one ($0{\cdot}9 \times 10^{-13}$ m/W), could be attributed to an uncertainty in the evaluation of the actual pump peak power (one could obtain a more accurate determination with a CW pump regime) and to possible effects of the dopant concentrations used for the fibre fabrication.

Conclusion: We have shown that gains as high as 45 dB for pump power around 2 W using SRS in SMF are possible. The pump power was generated at 1·18 μm in a first SMF by a multi-Stokes Raman process, the signal of a laser diode emitting at 1·24 μm being amplified by coupling both waves simultaneously into a second 2·5 km long SMF.

Acknowledgments: It is a pleasure to acknowledge the 'Fibres Optiques' and 'Semiconducteurs pour l'Optoélectronique' of the Laboratoire Central de Recherches de Thomson-CSF for the realisation of the SMF and of the laser diodes.

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19th July 1983

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HIGH-SPEED SCHOTTKY PHOTODIODE ON SEMI-INSULATING GaAs

Indexing terms: Semiconductor devices and materials, Photodiodes

A high-speed GaAs photodiode has been fabricated on a GaAs semi-insulating substrate. The photodiode has an active area of 8 μm × 15 μm and a bandwidth in excess of 9 GHz. This Schottky photodiodes is suitable for monolithic integration with other optoelectronic components.

One of the main advantages which integrated optoelectronic circuits (IOECs)[1] have over discrete circuits is the ability to achieve high frequency response due to a significant reduction of the parasitic reactances. Most of the work to date in developing high-speed photodetectors has been done on conductive substrates[2] and only a few reports have been published on photodetectors on semi-insulating (SI) GaAs 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 (FWHM) of 73 ps and 80 ps, respectively. In this letter, we report on a small area (8 μm × 15 μm) Schottky photodiode on SI GaAs substrate with a response time (FWHM) of less than 60 ps and rise and fall times of less than 30 ps and 50 ps, respectively.

The speed of photodetectors is given to a large extent by the transit time for the carriers to cross the depletion region and the diffusion of the minority carriers generated outside the high field region.[5] Owing to the high absorption coefficient of light in GaAs, photodiodes can be easily designed so that the diffusion tail effects do not pose any problems. Another possible limitation on the response speed speed is the $R_L(C_d + C_s)$ time constant, where R_L is the load resistance, C_s and C_d are the stray and depletion capacitances, respectively. The best performance (from speed and noise consideration) is obtained with a minimal capacitance. As a result the active area of the diode should be made very small and be determined from light coupling considerations. For small discrete diodes ($d < 30$ μm) fabricated on conductive substrate, the parasitic capacitance is the dominant one (the area of the bonding pad is bigger than the area of the diode). This problem can be solved by using SI substrates, where the bonding pad is located on the SI substrate, as we will demonstrate with the structure presented here.

A photograph of the Schottky photodiode is shown in Fig. 1 and a schematic cross-section can be seen in Fig. 2. The

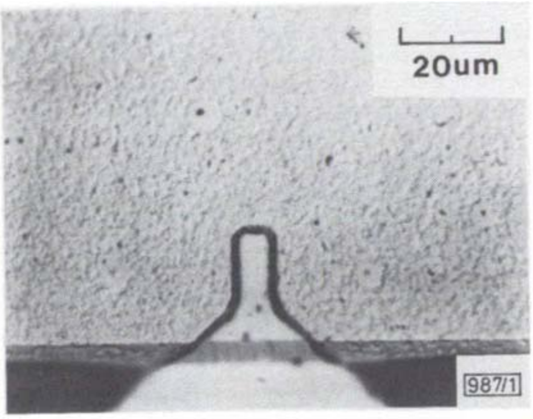

Fig. 1 *Photograph of Schottky barrier photodiode on SI substrate*
The active area is 8 μm × 15 μm

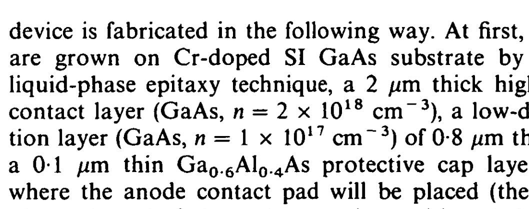

Fig. 2 *Schematic cross-section of photodiode*
Anode contact pad (Al) is on the left side and the cathode pad (AuGe/Au) is on the right side

device is fabricated in the following way. At first, three layers are grown on Cr-doped SI GaAs substrate by a standard liquid-phase epitaxy technique, a 2 μm thick highly *n*-doped contact layer (GaAs, $n = 2 \times 10^{18}$ cm^{-3}), a low-doped depletion layer (GaAs, $n = 1 \times 10^{17}$ cm^{-3}) of 0·8 μm thickness and a 0·1 μm thin $Ga_{0.6}Al_{0.4}As$ protective cap layer. The area where the anode contact pad will be placed (the left side in Fig. 2) is etched down 1·5 μm deep with a 1:8:8 (H_2SO_4 : H_2O_2 : H_2O) etching solution. Then, a thick photoresist layer is deposited (3 μm thick) to mask the active photodiode area and the cathode contact area against the following proton bombardment. The wafer is bombarded with 180 keV protons with a dose of 5×10^{14} cm^{-2} to isolate the anode bonding pad as can be seen in Fig. 2. Then, the wafer is thoroughly cleaned in HCl which etches the $Ga_{0.6}Al_{0.4}As$ cap layer thus leaving a clean GaAs surface for the Schottky electrode. The transparent Schottky diode contact is formed by evaporating a 150 Å thick Al layer. The anode contact area and the active diode area (8 μm × 15 μm) is defined by a photoresist mask which is used for the following three processing steps. At first, the 150 Å thick Al is etched and then the n^- GaAs top layer is etched down to the n^+ GaAs layer in the cathode contact area. As the third step, this photoresist mask is used to define the cathode metallisation (AuGe/Au) area through a lift-off technique. The Al anode contact pad is then reinforced and, finally, the AuGe/Au contact is alloyed at 420°C for 30 s.

The current/voltage characteristic of this 8 μm × 15 μm Schottky diode is shown in Fig. 3. The reverse breakdown

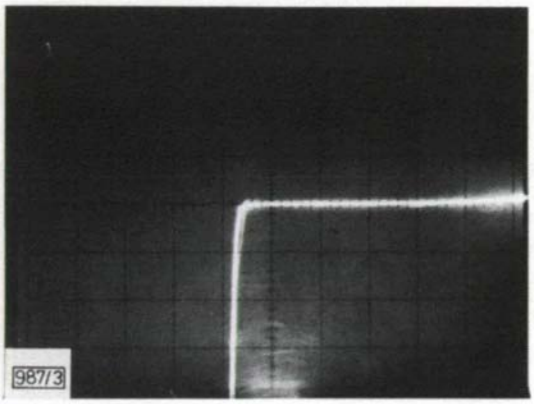

Fig. 3 *Current/voltage characteristic of Schottky diode*
Horizontal scale: 0·5 V/div; vertical scale: 1 mA/div

voltage is typically 5 V and the dark current is 5 nA at 2 V reverse voltage. The series resistance is typically 15 Ω. The external quantum efficiency is (without antireflection coating) around 15% at a wavelength of 840 nm. The high-speed response of the photodiode is measured using a pulse excited GaAlAs laser. The photodiode is mounted on a 50 Ω package and biased at a reverse voltage of 2 V. The laser diode (Hitachi HLP 3400) is driven by a comb generator (Hewlett Packard HP 33002) operating at a repetition rate of 100 MHz. A clean train of optical pulses is obtained and the width (FWHM) of the optical pulses is determined, by second-harmonic generation autocorrelation techniques, to be 25 ps. The photodiode response to the optical pulse train is observed in the time domain on a sampling scope (Tektronix S4) which has itself a rise time of 25 ps. The response is shown in Fig. 4.

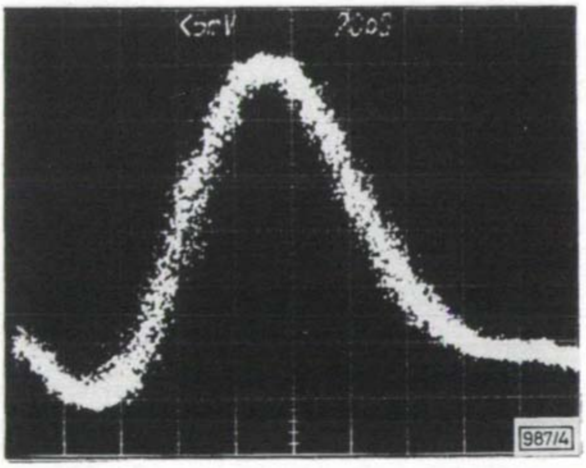

Fig. 4 *Pulse response of photodiode as measured with a sampling head (S4, 25 ps rise time)*
Diode is biased at a reverse voltage of 2 V. Horizontal scale: 20 ps/div

Rise and fall times are approximately 30 ps and 50 ps, respectively, and the pulse response has an FWHM of 60 ps. The response is mainly limited by the rise time of the sampling head and the finite pulse width of the laser light pulse, and the bandwidth of the Schottky diode is therefore well in excess of 9 GHz.

In conclusion, we have fabricated a Schottky photodiode on semi-insulating GaAs substrate, suitable for very high speeds and compatible for monolithic integration with other optoelectronic devices. The Schottky barrier photodiode has an active area of 8 μm × 15 μm and a rise time of less than 30 ps at a reverse voltage of 2 V.

This research was supported by the Office of Naval Research, the National Science Foundation under the Optical Communication Program and by the Army Research Office. One of the authors (Z. Rav-Noy) gratefully acknowledges the support of the Bantrell Fellowship.

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19th July 1983

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HIGH-PEAK-POWER ASYMMETRIC DOUBLE-HETEROSTRUCTURE (GaAl)As-GaAs INJECTION LASER

Indexing terms: Lasers and applications, Semiconductor lasers

An asymmetric double-heterostructure pulsed-power laser is described. This laser exhibits low-temperature sensitivity of optical power in the operating temperature range of −40 to +90°C. The threshold current is below 10 A at 90°C. The power loss at 40 A and 90°C operation is at least a factor of two less severe for this structure compared to that of the single heterostructure.

High-peak-power pulsed lasers, with a variety of structures, have been built and reported.[1–3] For the high-peak-power single-chip applications, the single-heterostructure[4] (SH) lasers are the more popular. A typical, commercially available SH laser has a peak power output of 9–10 W at 40 A and 0·02% duty cycle. Such a device has a reflective coating on one mirror and measures 230 μm in width and about 400 μm in length. Operating these devices at elevated temperatures decreases the peak power output and the dynamic range of the drive current due to the increase of threshold current.

The object of this letter is to report the performance of lasers with inherently low threshold current and low temperature sensitivity of the optical power. However, the same operating conditions (i.e. same maximum current and duty cycle) as SH lasers are maintained. To achieve this, we chose an asymmetric double-heterostructure[5] (ADH) laser. Four sequential layers $N^+p^+Pp^+$ are grown by liquid-phase epitaxy (LPE) on n^+-GaAs substrate. The first layer, N^+-$Al_xGa_{1-x}As$ with $x \simeq 0{\cdot}1$, is grown 12 μm thick. The layer is doped with tellurium to a concentration of the order of 6×10^{18} cm^{-3}. The second layer, p^+-GaAs, is the active layer and is heavily doped with silicon. The third, a P-$Al_yGa_{1-y}As$ cladding layer, with $y = 0{\cdot}35$, is 3 μm thick. The fourth layer, p^+-GaAs contact layer, is 29 μm thick. Germanium is used as the dopant in the last two layers. However, zinc is diffused into the p^+ contact layer to enhance low ohmic contact resistance. The wafer is thinned, metallised, cleaved and sawn into chips with final dimensions of 230 μm width and 400 μm in length. One of the mirrors is coated with an Al_2O_3 antireflection coating, followed by an aluminium reflection coating. The finished devices are packaged in headers and hermetically sealed.

A fair number of devices in the range of 9–10 W optical peak power output at 40 A have been obtained. A small number of devices reached the 10–12 W range. The lasing