Novel GaAs photodetector with gain for long wavelength detection

E. S. Harmon, D. T. McInturff, M. R. Melloch, and J. M. Woodall
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907-1285

(Received 10 October 1994; accepted 11 November 1994)

A novel photodetector based upon annealed low temperature molecular beam epitaxy GaAs capable of detecting wavelengths out to 1.5 μm has been developed. The device utilizes a photoconductive detector with a high photo-generated carrier lifetime to transit time ratio in order to achieve a high internal gain. The sensitivity to illumination with photons of sub-bandgap energies is achieved due to the internal photo-emission from the semi-metallic arsenic precipitates. The device exhibits higher gains at lower input powers because the effective carrier lifetime is longer for lower input power levels. This variation in carrier lifetime can be explained in terms of the effectiveness of the arsenic precipitates as recombination centers as a function of optical power levels.

I. INTRODUCTION

Low temperature molecular beam epitaxy (MBE) GaAs has emerged as a material system with a number of unique properties. In general, these materials exhibit short carrier lifetimes,[1] and, when annealed, very high resistivity.[2] In addition, McInturff *et al.*[3] have shown that annealed low temperature MBE GaAs (referred to as GaAs:As) exhibits reasonable sensitivities to illumination with photons of sub-bandgap energies. Unfortunately, the low absorption coefficient at longer wavelengths leads to relatively poor responsivities. In this article, a high gain GaAs:As photodetector is presented which improves the overall detector responsivity, allowing for improved long wavelength response.

A photoconductive detector is capable of high internal gains when the photo-generated carrier lifetime is much longer than the carrier transit time across the device. A typical MSM photoconductive detector arrangement is shown in Fig. 1. The spacing between the interdigitated fingers determines the transit time, which is ~10 ps/μm for electrons in GaAs traveling at their saturation velocity. Normal, undoped GaAs:As exhibits carrier lifetimes less than 20 ps,[1,4,5] so the maximum possible internal gain for a metal–semiconductor–metal (MSM) photoconductive detector with 1 μm finger spacing is two (the average electron can transit between the metal fingers twice before it recombines). Note that this device requires low resistance ohmic contacts—Schottky contacts will suppress injection of electrons into the device, allowing carriers to travel between the fingers only one time. If it is possible to produce a GaAs:As material with longer carrier lifetimes (~1 ns), then internal gains as high as 100 would be feasible.

While there still exists controversy concerning the source of the unique properties of GaAs:As, the Schottky barrier model[6] appears to account for all observed properties. The insulating nature of GaAs:As can be attributed to the depleting action of the Schottky barriers at the buried semi-metallic arsenic precipitates. It also appears that the carrier lifetime may be described in terms of recombination at the arsenic precipitates.[5] Recent results of Si-doped GaAs:As show that the conductivity of this material may be varied over six orders of magnitude depending upon the post growth anneal conditions.[7] These results also demonstrate a threshold condition where slight variations in the anneal temperature result in a large change in the conductivity. This threshold condition occurs at the point where the depletion regions surrounding the arsenic precipitates just barely overlap. Further annealing increases the spacing between precipitates, reducing the overlap of the depletion regions. This allows conducting channels between the precipitates to be formed, resulting in large overall conductivity increases. Similar conductivity increases can be achieved if the Schottky diodes at the precipitates are forward biased, decreasing the depletion region diameter. This forward bias could be achieved by illuminating the open circuited Schottky diodes with photons of energies greater than the Schottky barrier height.

II. EXPERIMENT

The film used in this study was grown in a Varian Gen II MBE system with As_2 for the group V source and elemental Ga for the group III source. The beam equivalent pressure ratio of As_2 to Ga was ~20. The structure consists of a 0.5 μm undoped GaAs layer grown at 600 °C followed by the 0.75 μm GaAs active region grown at 250 °C with a Si doping of 1×10^{18} cm^{-3}. A post growth anneal of 750 °C for 30 s was performed in a rapid thermal annealer. Interdigitated AuGe:Ni:Ti:Au contacts were alloyed into the GaAs:As film, providing the ohmic source and drain contacts. While finger spacings of 1, 2, and 4 μm were studied, the results presented here refer to devices with a finger spacing of 1 μm.

The steady state optical characteristics were examined with a titanium sapphire laser. Figure 2(a) shows a typical current-voltage curve for this device under 850 nm illumination. The device current is linear with applied voltage for low voltages and saturates for high voltages, consistent with the electron velocity becoming saturated for high electric fields (>10 kV/cm). Figure 2(b) shows the same device with 950 nm illumination (photons with ~120 meV less than bandgap energy), showing very similar characteristics with approximately an order of magnitude less responsivity. Figure 3 shows the responsivity versus wavelength of this same device. It is important to note that the responsivity varies considerably with input power, which implies that the gain of the device also varies with input power. Thus, the effective car-

 0734-211X/95/13(2)/768/3/$6.00

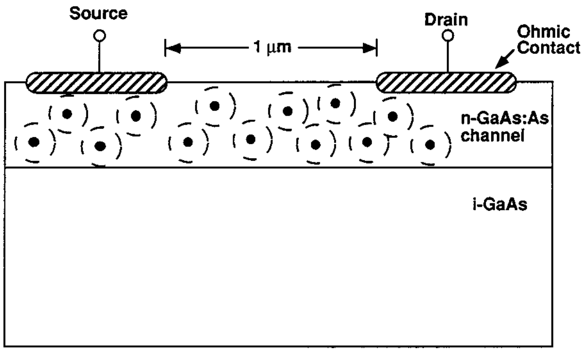

FIG. 1. Cross Section of MSM photoconductor, showing depletion regions surrounding arsenic precipitates in the channel.

rier lifetime must be longer for lower power illumination in order to achieve the device gains observed in Fig. 3.

Longer wavelength operation was studied with a 1000 W white light source filtered with a monochromator. The resulting responsivities exhibited an order of magnitude decrease from 950 nm to 1300 nm, and an additional order of magnitude decrease for 1500 nm illumination. The resulting responsivities for ~10 μW input powers was 0.1 A/W and 0.01 A/W for 1300 nm and 1500 nm illumination respectively.

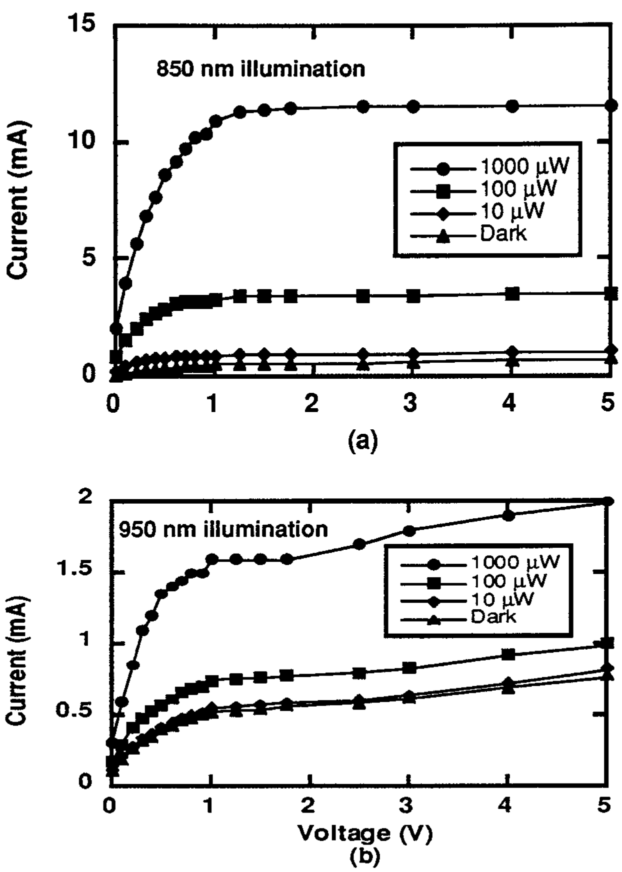

FIG. 2. Current-voltage characteristics of the MSM photoconductive detector with 1 μm finger spacing under (a) 850 nm and (b) 950 nm illumination

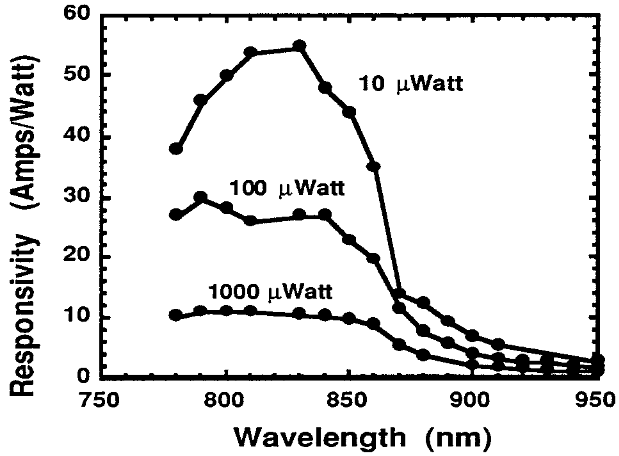

FIG. 3. Responsivity versus wavelength of the MSM photoconductive detector with 1 μm finger spacing.

In addition, the time resolved characteristics were measured for pulsed laser illumination. A Coherent Mira 900F titanium sapphire laser producing pulses of ~100 fs duration at a repetition rate of 73 MHz was used for these measurements. A Pockels cell pulse selector from Conoptics was utilized to reduce the repetition rate to ~4 kHz. The device was mounted in a microwave package and measured with a Hewlett Packard 54120T sampling oscilloscope. The device package and bias tee used limited the bandwidth to ~10 GHz. Figure 4 shows the time evolution of the voltage response of the device under two levels of illumination. It can clearly be seen that the tail of the response is much more important for the low power illumination. For high power illumination, a considerably faster response is realized, and the tail is negligible. Note that these results complement those presented in Fig. 3—the average photogenerated carrier has a longer effective lifetime under lower power illumination. The average carrier lifetime will be proportional to

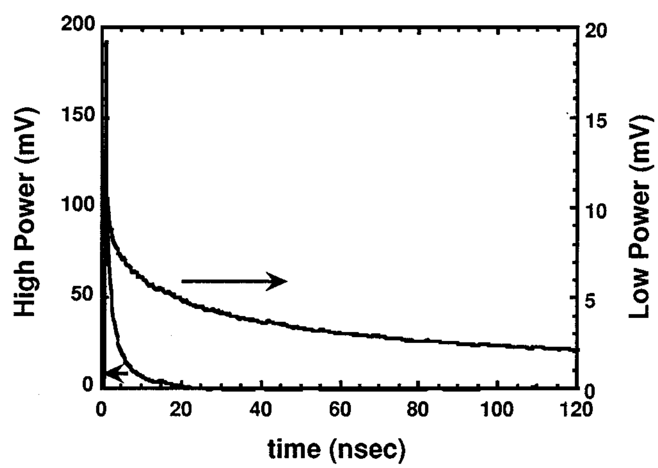

FIG. 4. Pulse response of MSM photoconductive detector. The high power pulse energy was ten times larger than that of the low power pulse. Note also that the voltage scale for the high power pulse is ten times larger than that for the low power pulse. The low power curve shows a much longer effective carrier lifetime.

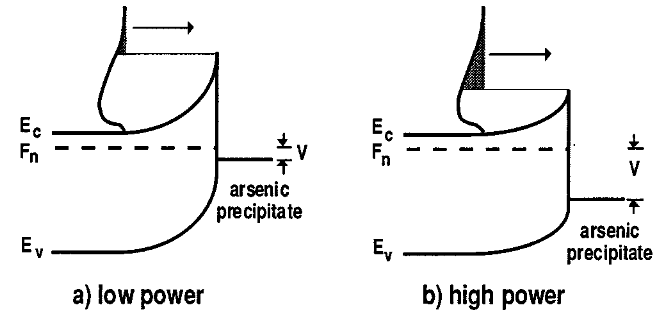

FIG. 5. Band diagrams of the GaAs region near the arsenic precipitates. Under low power illumination (a) the Schottky diode formed by the precipitate-GaAs interface is only slightly forward biased, resulting in only a small proportion of the electrons having enough energy to surmount the Schottky barrier (shaded region in diagram). Under high power illumination (b) a much larger proportion of the electrons have enough energy to surmount the barrier.

the area under the curves in Fig. 4, as photoconductivity is proportional to the carrier lifetime. A reasonably fast (<10 ns) response is achieved for high power illumination, while a considerably slower response is achieved for low power illumination. Here we see direct evidence of a simple photoconductive detector tradeoff—higher gain requires a longer lifetime and hence a slower response.

Finally, we consider whether the responses shown could be attributed to the effects of deep level recombination centers (possibly arsenic antisites). It is true that the occupancy of such trap levels can be strongly affected by doping, conceivably resulting in considerably longer lifetimes than in undoped material. However, Shockley–Rheed–Hall (SRH) recombination at these traps cannot explain the variation in effective lifetime with optical power. At higher input power levels, it may be possible to saturate SRH centers, but this would result in a longer effective lifetime. Thus, if the responses were due to SRH recombination, we would expect a higher gain for higher power levels—the opposite of that observed here. Recombination at buried Schottky barriers, however, would explain the trends observed here. The effective recombination rate for recombination at the arsenic precipitates would be proportional to the ratio of the number of carriers that have enough energy to surmount the Schottky barrier to the total number of carriers. At low input power levels, the Schottky junction is only weakly forward biased, resulting in only a small fraction of the total carriers having enough energy to reach the precipitate. At higher input power levels, the potential barrier to the precipitate is further reduced, resulting in a larger fraction of the total carriers reaching the precipitate, and hence a much higher effective recombination rate (see Fig. 5).

III. CONCLUSIONS

We have shown that it is possible to produce a long wavelength detector in low temperature growth GaAs:As that has high responsivity due to high internal gain. Since this device operates as a photoconductive detector, high internal gains are obtained as a direct result of a long effective carrier lifetimes. These longer carrier lifetimes result in slower device responses as a direct result of the tradeoff between speed and gain in photoconductive devices. For applications requiring high responsivity, some speed must be sacrificed in order to reach the gain desired. In addition, since the effective lifetime of these devices is a function of the input optical power, the output response is a nonlinear function of input power.

ACKNOWLEDGMENT

This work was supported by the Air Force Office of Scientific Research under Grants Nos. F49620-93-1-0031 and F49620-93-1-0388

[1] S. Gupta, J. F. Whitaker, and G. A. Mourou, IEEE J. Quantum Electron. **QE-28**, 2464 (1992).

[2] F. W. Smith, A. R. Calawa, Chang-Lee Chen, M. J. Mantra, and L. J. Mahoney, IEEE Electron Devices Lett. **EDL-9**, 77 (1988).

[3] D. T. McInturff, J. M. Woodall, A. C. Warren, G. D. Pettit, P. D. Kirchner, and M. R. Melloch, Appl. Phys. Lett. **60**, 448 (1992).

[4] E. S. Harmon, M. R. Melloch, J. M. Woodall, D. D. Nolte, N. Otsuka, and C. L. Chang, Appl. Phys. Lett. **63**, 2248 (1993).

[5] E. S. Harmon, Ph.D. Thesis, Purdue University, 1994.

[6] A. C. Warren, J. M. Woodall, J. L. Freeouf, D. Grischkowsky, D. T. McInturff, M. R. Melloch, and N. Otsuka, Appl. Phys. Lett. **57**, 1331 (1990).

[7] N. Atique, E. S. Harmon, J. C. P. Chang, J. M. Woodall, and M. R. Melloch, J. Appl. Phys. **77**, 1471 (1995).