METAL-SEMICONDUCTOR-METAL PHOTODETECTORS ON INTERMEDIATE TEMPERATURE MBE GROWN GaAs FOR LIGHTWAVE/MILLIMETER-WAVE APPLICATIONS

Arthur Paolella [1], Gregory Tait [2], Paul Cooke [3], Bahram Nabet [4], Brad Tousley [2]

[1] US Army CECOM, Research Development and Engineering Center, Ft. Monmouth, NJ 07703
[2] US Military Academy, Photonics Research Center, West Point, NY 10996
[3] Army Research Laboratory, Physical Sciences Directorate, Ft. Monmouth, NJ 07703
[4] Drexel University, Electrical Engineering Dept., Philadelphia, PA 19104

Abstract

Intermediate growth temperature (IGT) GaAs GaAs Metal-Semiconductor-Metal (MSM) photodetectors enables an optimal combination of large dynamic range and speed. In addition these devices are suitable for monolithic integration. The static and temporal response of GaAs MSMs grown by Molecular Beam Epitaxy (MBE) at 350° C has been measured.

Introduction

MSM photodetectors fabricated from low-temperature (LT) (200° C) MBE GaAs have very low dark current due to the large density of point defects and consequent reduction in carrier lifetime compared with normal growth temperatures of 600° C[1]. These devices also have poor optical responsivity due to constraints of active area leading to poor dynamic range. Analog microwave systems however require a large dynamic range and high speed for optical signal distribution. Intermediate-growth-temperature (IGT) GaAs has previously been shown to exhibit improved dynamic range under static conditions [2]. Here high speed optical testing is used to assess such devices for microwave applications. A photodetector is needed whereby large dynamic range is obtained while maintaining the speed required to distribute microwave signals. We propose here that IGT GaAs may be well suited for applications requiring an optimal combination of moderate bandwidth, high responsivity, and low dark current.

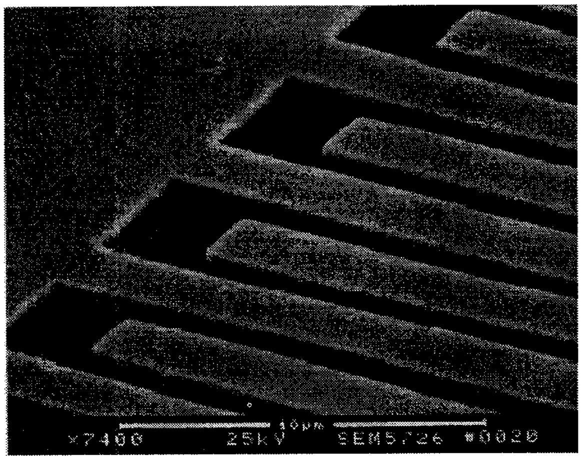
Device Design and Fabrication

To obtain good sensitivity the transit time of the optically generated carriers should be no more than the recombination lifetime of the material. Therefore to take advantage of the carrier lifetime of low temperature material which is about 1 ps, the device size should be in the tens of nanometers. This may cause the device to be RC time constant limited and hence force the choice of very small device area. These design constraints limit the suitability of LT GaAs photodetectors in many microwave system applications. For this study a moderately small but functionally useful size was determined for the IGT devices based on processing limitations and test facilities.

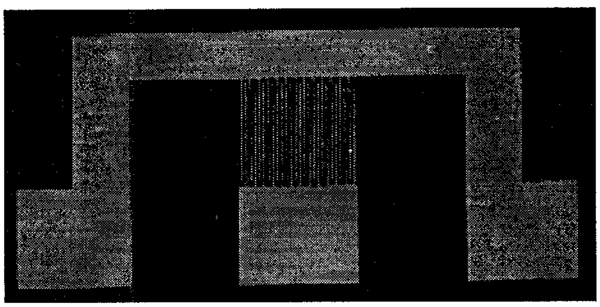
The GaAs material was grown on semi-insulating (100) GaAs substrates using MBE at a temperature of 350° C. Devices were then formed on the surface of the undoped IGT-GaAs. The interdigitated pattern was formed by electron-beam lithography and Ti/Au Schottky metal deposition. The device selected for this study had finger widths and spacing of 1 µm and an active area of 50 µm x 50 µm. The GaAs active layer was 1.5 µm thick. A SEM photograph of a device is shown in Fig. 1 (a). The devices were designed with contact pads in a ground-signal-ground configuration to facilitate high frequency testing using co-planar probes (with a pitch of 100 µm) as shown in Fig. 1 (b). Figure 2 shows the measured dark current and photoresponse (1 mW at 850 nm) as a function of bias voltage from 1 to 10 Volts. The dark current remains below 10 nA up to 8.0 Volts, a

0-7803-3246-6/96/$5.00 © IEEE

typical bias range. Figure 2 also shows the dynamic range defined here as the difference between the photoresponse and the dark current. The dynamic range is greater that 4 orders of magnitude over most of the bias range which is a 2.5 times improvement over low growth temperature material [2]. The responsivity, defined here as the photocurrent per absorbed photon is 0.44 mA/mW at 10 volts bias.



(a)



(b)

Figure 1. Scanning electron micrographs of MSM photodetector. (a) close up view of finger structure (b) co-planar probe ground-signal-ground configuration

Experimental Results

Experimental measurements were made of the temporal response of the MSM detector to optical impulses generated by a mode locked $Ti:Al_2O_3$ laser with 80 fs pulse width. With a test system bandwidth of 20 GHz, the microwave test electronics are capable of resolving the resulting electrical pulses from the photodetector to an accuracy of approximately 20 ps. Testing consisted of measurements of the pulse response as a function of DC bias (2 V - 13 V) and optical pulse energies (20 pJ - 600 pJ). The laser light wavelength was nominally 850 nm.

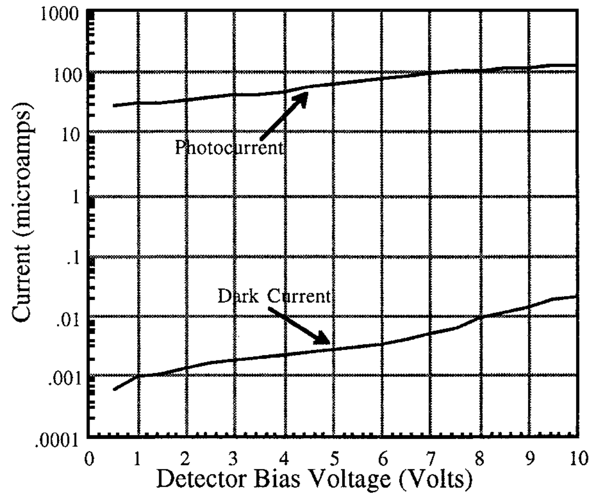


Figure 2. Dark current and photoresponse as a function of bias voltage. The photoresponse is measured with 1 mW of optical power at 850 nm.

The normalized pulse response at three pulse energies is shown in Fig 3. The response was normalized to the maximum voltage amplitude measured at each pulse energy. The fall times increase from 400 ps to 700 ps as the optical energy increases. The increase at high optical intensities is due to a high concentration of optically generated carriers screening the applied electric field or saturation of the deep level traps in the intermediate temperature (IT) GaAs.

The fall times were measured as a function of bias voltage as shown in Fig. 4. The fall times also show a strong dependence on the bias or electric field for the lower optical energies. At 45 pJ the fall time changes from 422 ps to 242 ps with bias varying from 2 to 13 volts. Similar fall time changes are seen at 110 pJ. At 230 pJ optical carrier density is high enough to eliminate the effect of the external electric field over most of the bias range. Only a small decrease is observed at voltages beyond 10 volts.

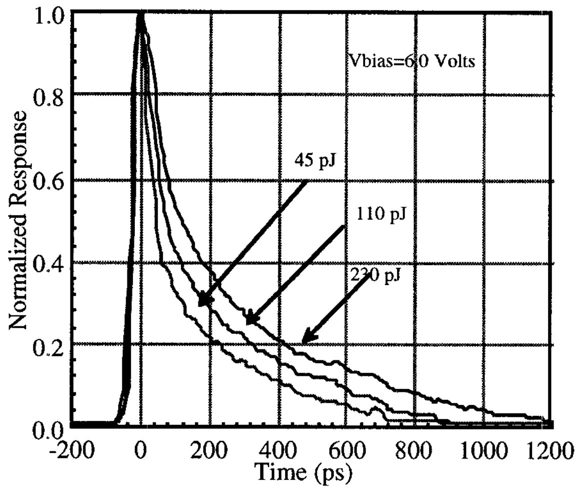


Figure 3. Normalized pulse photoresponse of MSM photodetector at optical energies of 45, 110 and 230 pJ

The observed reduction in fall times with increasing DC bias voltage is primarily due to the decrease in carrier transit time, particularly the hole transit time which is responsible for the long decay times of the photoresponse. The hole transit time is dictated by the hole drift velocity which rises slowly to its saturated value with increasing electric field. This effect is more pronounced at lower optical pulse energies since the electric field is less affected by the optically generated carriers. Over the entire range of DC bias voltages and optical pulse energies, typical fall-times (90% to 10%) range over 200 ps to 800 ps

The full-width, half-maximum (FWHM) values as a function of bias voltage are shown in Fig. 5. They range over 50 ps to over 200 ps, corresponding to bandwidths of 2.5 GHz - 10 GHz. The fastest device achieved 50 ps FWHM at a DC bias voltage of 6 V and optical pulse energy of 20 pJ. The optimum response at each optical pulse energy occurs at 6.0 Volts. The most sensitive response is at 230 pJ. the relatively broad pulses at the low and high bias voltages coincide with low electric fields and rapidly growing pulse amplitudes.

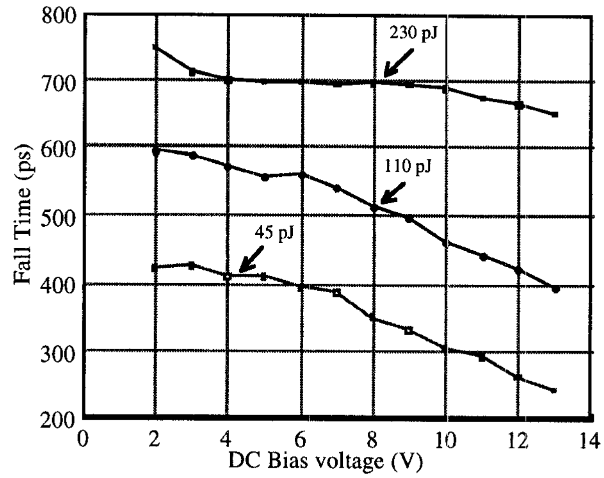


Figure 4. Fall time as a function of voltage at optical energies of 45, 110 and 230 pJ.

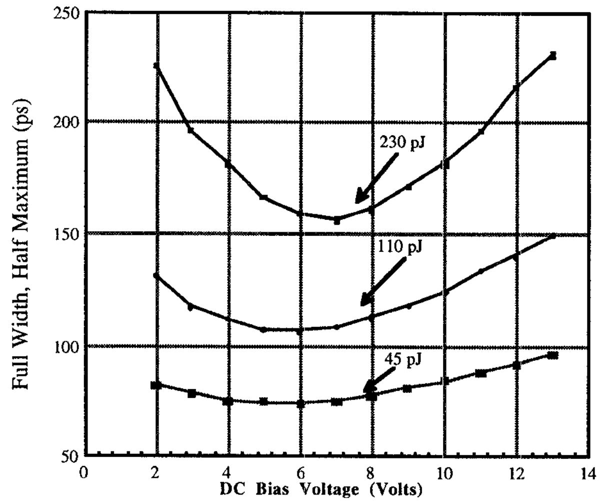


Figure 5. Full Width Half Maximum values as a function of voltage at optical energies of 45, 110 and 230 pJ.

The temporal response of this device is longer compared with LT GaAs devices, however it exhibits superior responsivity. The responsivity of the device was also determined. Optimum responsivity, defined here as peak voltage per absorbed optical pulse energy, is obtained by reducing the optical pulse energy and maximizing the applied bias voltage. Peak voltages (switching voltages) as a function of DC bias for the same three optical pulse energies are shown in Fig. 6. At 12 V bias and 20 pJ optical energy, the responsivity is 80 mV/pJ. It is projected that responsivities well above 100 mV/pJ can easily be achieved at higher biases and lower optical energies.

The switching efficiency can be determined from the ratio of the change in the switching voltage to the bias voltage. The change in voltage can be modeled as

$$\Delta V(t=0+) = V_{dc}\left[1 - \frac{R_{light}(V_{dc},P_{inc})}{R_{dark}(V_{dc})}\right] = \\ = V_{dc}\frac{\Delta\sigma}{\sigma} = V_{dc}\frac{q\lambda\eta}{hc}\left[\frac{\mu_e+\mu_h}{\sigma}\bullet\frac{\Delta t_{pulse}}{AW}\right]P_{inc} \quad (1)$$

Therefore the switching efficiency of the device can be expressed as

$$\eta_{switching} = \frac{\Delta V}{V_{dc}} = \frac{q\lambda\eta}{hc}\left[\frac{\mu_e+\mu_h}{\sigma}\bullet\frac{T}{AW}I_{ph}\right]\frac{P_{ave}}{I_{ph}} \\ = \frac{q\lambda\eta}{hc}G_{pulse}\frac{1}{R} \quad (2)$$

where

$$R = \frac{I_{ph}}{P_{ave}} = \frac{q\lambda\eta}{hc}G_{dc} \quad (3)$$

is the responsivity under constant illumination. G_{pulse} and G_{dc} represent the photoconductive gain under pulsed and constant illumination.

At 4.0 Volts, the peak-to-peak voltages switched across the device are 13 %, 25 %, and 48 % of the bias voltage for optical pulse energies of 45 pJ, 110 pJ, and 230 pJ, respectively. At 22 V DC bias voltage and 570 pJ optical pulse energy, the switched voltage amplitude is a remarkable 15.2 V, which represents a 69 % switching efficiency.

Conclusion

The IGT MSM photodetector is a versatile device with many desirable attributes and is amenable to planar integration in optoelectronic integrated circuits.

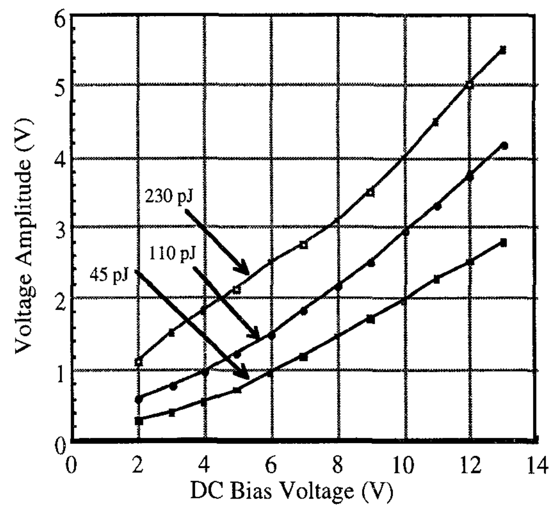


Figure 6. Peak voltage amplitude as a function of bias voltage.

It exhibits low dark current due to its blocking contacts, broad bandwidth, and large responsivity. The experimental results reported here demonstrate that this device efficiently switches large voltages under high optical pulsed power and possesses broad bandwidths exceeding 10 GHz. With further improvements in the high-speed response made by optimizing growth temperature and device geometry, immediate impact can be made on millimeter wave systems such as the optically controlled phased-array antenna. Research challenges include physical device modeling of the detailed carrier transport mechanisms in undoped GaAs which is presently being addressed.

References

1. Look, D., Waters, M., Stutze, C., Brierly, S., *Applied Physics Letter* 60,1993.

2. B. Nabet, A. Paolella, M. Lemuene, R., Moerkirk and L-C Lui, "Intermediate Temperature Molecular Beam-Epitaxy Growth for Design of Large-Area Metal-Semiconductor Metal Photodetectors," *Appl. Phys. Lett.* 64 (23), pp. 3151-3153, June 1994.