Manufacturing of 10 GHz InGaAs/InP p-i-n Photodetectors in GaAs Wafer Fabrication Facility

Debdas Pal, Lisza Elliot, and James Carter

MACOM, 100 Chelmsford Street Lowell, MA, 01851
e-mail: debdas.pal@macom.com, Phone: +1 978-656-2581

Keywords: Photodetectors, InGaAs, InP, High speed, responsivity, dark current, sensitivity

Abstract

The demand of InGaAs/InP p-i-n photodetectors operating at around 1300 nm - 1550 nm has increased significantly. In order to increase production volume, it is necessary to manufacture detectors on 4 inch InP substrates. The GaAs IC production fab is an ideal place to manufacture photodiodes on 4 inch InP substrates using existing equipment. The photodetectors with very low dark current (0.1 nA) and bandwidth of about 10 GHz have been manufactured successfully in the GaAs IC fab. The devices passed reliability test and the process has been released for production.

INTRODUCTION

A photodetector is a solid state sensor which converts light into an electrical signal. Light absorption in a semiconductor generates electron hole pairs. These pairs produced in the depletion region or within the diffusion length are separated by the electric field leading to a current flow in the external circuit. Semiconductor photodetectors are made from different types of semiconductor materials such as Si, Ge, GaAs, GaInAs, InAs, InSb and many more. The selection of the material depends on the application. For example, telecommunication systems require fast detectors operating at 1.3 to 1.55 µm to transfer data at high speed with low fiber loss. $In_{0.53}Ga_{0.47}As$ material lattice matched to InP is the most suitable compound for this application [1]. There are different types of photodetectors that can be manufactured using this material such as; photovoltaic, photoconductive, avalanche photodetectors, and phototransistors. However, a p-i-n photodiode is one of the most common photodetectors because the depletion region thickness (i- the intrinsic layer) can be adjusted to obtain different speeds and quantum efficiencies. The p-i-n photodiode offers the advantages of lower dark current, larger frequency bandwidth [2] and simpler driving circuitry over avalanche photodiodes operating in the same wavelength region. Generally, p-i-n photodiodes do not provide any internal gain, however, an optimal combination of a photodiode with a low noise large bandwidth transistor may produce a high performance optical receiver. The demand of these products has increased significantly in recent years. It is necessary to manufacture these on 4 inch wafers to increase the volume and satisfy the market demand with reasonable cost. The manufacturing process of 10 GHz InGaAs/InP p-i-n photodiode was developed without any capital investment.

DEVICE STRUCTURE AND FABRICATION

The p-i-n photo detector could be a planar device with zinc diffusion [3] or a mesa device with epitaxial p-type contact layer (without zinc diffusion) [4]. Generally, the planar type photodiodes provide lower dark current than the mesa devices. This is due to the presence of a passivation layer away from the active interface in planer photodiodes. The mesa type devices do not require extra zinc diffusion process, however the surface passivation is very critical. These devices could produce higher dark current and fail long term reliability due to exposed active mesa surface to the nitride passivation layer. Different types of pre-cleans and passivation layers were studied to reduce the dark current [5, 6]. The specifications of the products determine the type of the device and process technology. In order to manufacture devices with very low dark current (pA) and high breakdown voltage, planar devices with zinc diffusion process was developed.

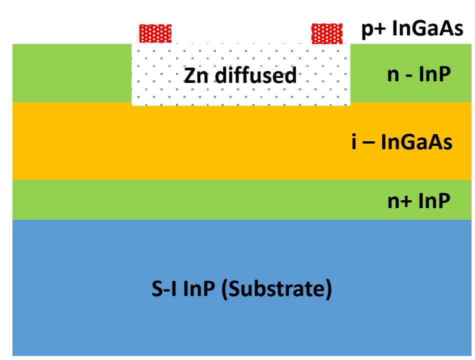

Fig. 1. Epitaxial structure of P-I-N diode.

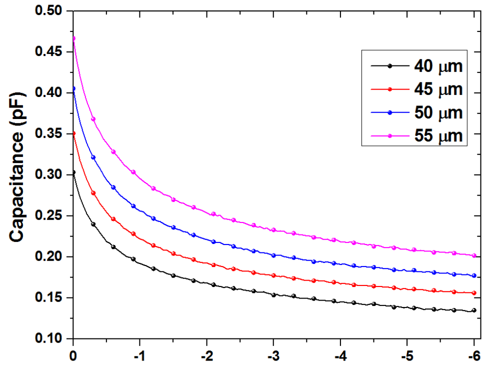

Fig. 2. Variation of capacitance of p-i-n diodes with different diameters.

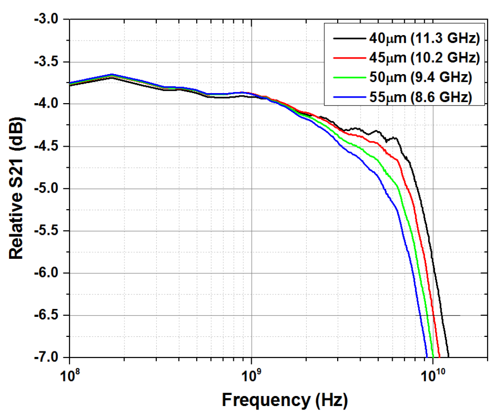

Fig. 3. High frequency response of p-i-n photodiodes with different diameters measured at 5 V.

Fig. 1 shows the epitaxial layer structure of a planar p-i-n photodiode. It contained four layers (1) n+ InP bottom contact layer, (2) InGaAs i layer (undoped), (3) InP diffusion layer and (4) InGaAs top contact layer. All the layers were grown by MOCVD on 4 inch semi-insulating InP substrates. The photolithography masks for different process steps were designed to manufacture the devices with a certain diameter and pad configuration.

In the fabrication process, silicon dioxide layer was used as a mask for selective zinc diffusion. Different wet chemical etch processes were developed to create InGaAs ring contact layer and mesa structure. The mesa etch process provided cylindrical mesas with smooth side walls, which helped to obtain lower dark current and capacitance. The Ti/Pt/Au p-ohmic contact and AuGeNi/Au n-ohmic contact were deposited by electron beam evaporation and annealed using rapid thermal annealing system. Silicon nitride was used as passivation layer as well as an antireflection coating. The thickness of the layer was designed to obtain lower reflection from the optical window on the device. Thick BCB layer around mesa was used to reduce parasitic capacitance as well as to protect the mesa.

RESULTS AND DISCUSSION

The critical device parameters of a p-i-n photodiode are capacitance, dark current, responsivity, breakdown voltage, and speed. The speed of the devices is limited by the carrier transit time, RC time constant, diffusion current, carrier trapping at heterojunctions and packaging. The carrier transit time depends on i layer thickness. The lower i layer thickness would produce higher speed but it would reduce the responsivity and increase capacitance. Devices with lower series resistance and capacitance would also show high speed. Lower capacitance can be achieved by reducing the device diameter, however, it could decrease the responsivity due to reduction of the absorption area. It could also complicate the alignment of the fiber to the device. Therefore, it is necessary to optimize the device area and i layer thickness to obtain certain speed and responsivity. In order to optimize the performance, devices with different diameters were fabricated. The capacitance of the devices was measured using a Keithley capacitance meter at different bias voltages. Fig. 2 shows the variation of capacitance as a function of reverse bias of the devices with different diameters but with constant i layer thickness. The capacitance of the devices is increased with the increase of the diameter as expected. The reduction of capacitance with the increase of reverse bias is due to the increase of depletion width. An Agilent high speed test system was used to measure the bandwidth of the devices. The measured 3dB bandwidths of the devices are shown in Fig. 3. The bandwidth is decreased with the increase of the capacitance, which is primarily due to increase of the RC time constant. The devices with 45 μm diameter showed 10.2 GHz bandwidth.

The responsivity of a photodetector is defined by the ratio of the photocurrent to the optical power. The responsivity was measured by directing a laser light of 1330 nm on to the device through an optical fiber and light wave probe. The boxplot of responsivity of the devices is shown in Fig. 4. No significant difference between the responsivities measured at 2V and 5V was observed which indicates that the devices can be operated at 2V without impacting the performance. The responsivity of the devices was about 0.98 mA/mW.

The quantum efficiency is the number of electron-hole pairs generated per incidence photon, which is related to responsivity as described in equation:

$$R = \eta \times \frac{q\lambda}{hc}$$

Where R, η, λ, h, and c are the measured responsivity, quantum efficiency, incident light wavelength, Planck constant, and speed of light. The calculated quantum efficiency was about 88% with the incident wavelength of

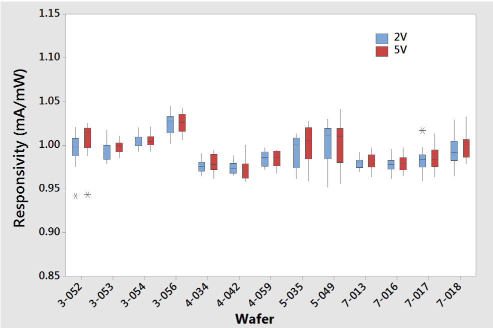

Fig. 4. Responsivity at 1330 nm of the p-i-n devices.

1330 nm and responsivity of about 0.95 mA/mW. The high quantum efficiency revealed that the process and the epitaxial structure are of good quality. A keithley production test stand

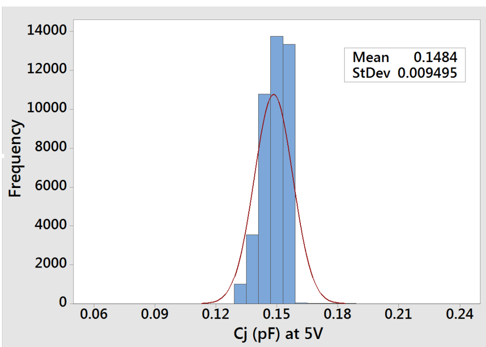

Fig. 5. Distribution of capacitance measured at 5 V.

was used to test devices of 45 µm diameter on a full wafer. Figure 5 shows the distribution of capacitance of about 42000 devices in a wafer. The average capacitance measured at 5V was about 148 fF with a standard deviation of about 9.5 fF. The tight distribution of the capacitance indicated high quality of the epitaxial wafer (uniform i layer thickness and doping) as well as the manufacturing process. The dark current of the devices measured at 5 V is shown in Fig. 6. The average dark current was about 0.1 nA. The lower dark current of these devices is primarily due to high band gap InP cap layer, which reduced generation recombination current

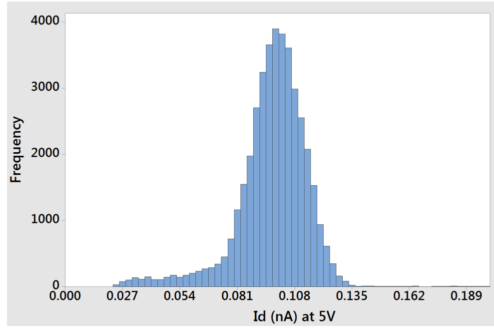

Fig. 6. Dark current distribution measured at 5 V.

and the diffusion current. It is also due to zinc diffusion process, which helped to reduce the surface leakage.

The sensitivity of a photodiode is defined as the minimum optical power necessary to achieve a required BER (bit error rate). In order to measure sensitivity several devices were packaged in 2.5 GHz p-i-n-TIA package. The sensitivity was found to be around -30.6 dBm. These devices passed reliability test and the process has been released for production.

Conclusion

The manufacturing process of 10 GHz InGaAs planar p-i-n photodiodes has been developed successfully. The critical device parameters such as dark current, capacitance, responsivity, speed and sensitivity were measured. The characteristics of the devices are similar to the devices available in the market. These devices also passed the reliability test and the process has been released for production.

Acknowledgement

The authors wish to acknowledge Hawk Tsai for his valuable support during development of the process. They are also grateful to Craig Pastrone for his continuous encouragement and support. Fredrick Hardy, Mark Dewilde, and Ross Keesler are also acknowledged for their support in the test and post fabrication process.

References

[1] K. Yamaguchi, H. Kitasagami, M. Kawai, I. Amemiya, T. Touge, H. Tamada, M. Kokado, and M. Sugimoto, IEEE Select. Areas Commun., 6 pp. 460-467, April 1998.

[2] T.P Pearsall, and M.A. Pollack, “Semiconductor and semimetals”, pp 193, 22 D Academic Press, New York, 1985.

[3] O. K. Kim, B. V, Dutt, R. J. McCoy, and J. R. Zuber, IEEE J. Quantum Electron., QE-21, pp. 138 – 143, Feb. 1985.

[4] G. H. Olsen, “IEEE Electron. Device Lett., EDL- 2, pp. 217 - 219 Sept. 1981.

[5] H.J Stocker and D.E Aspnes, Appl. Phys. Lett. 42, pp. 85 1983.

[6] R. Yeats and K. Vossonneck, Appl. Phys. Lett. 44, pp 145 1984.

ACRONYMS

MOCVD: Metalorganic Chemical Vapor Deposition
BCB: Benzocyclobutene