Extended Abstracts of the 16th (1984 International) Conference on Solid State Devices and Materials, Kobe, 1984, pp. 591-594

C-10-4

Long-Wavelength $In_{0.53}Ga_{0.47}As$/InP PIN Photodiode

Li Si-hai, Zhang Yan-bin, Zhang Chong-ren,
Zhang Sheng-qiong and Chen Xiao-jian

Nanjing Solid State Devices Research Institute

Nanjing, China

The design principles of $In_{0.53}Ga_{0.47}As$/InP PIN photodiode with front-illuminated configuration are discussed through evaluation and comparision with the back-illuminated configuration in advantages and disadvantages. Analysis is emphasized on the significance of junction-depth control and removal of high-recombination layer on photosensitive surface. Some special measures are used in the diode fabrication and the best results obtained are $J_D = 3.5 \times 10^{-6} A/cm^2$, C= 0.7pf, η = 85%, and $\Delta\tau \leq$ 100ps at -10V bias.

Introduction

The performances of $In_{0.53}Ga_{0.47}As$ PIN photodiode, one of the key devices used in long-wavelength optical-fiber communication, are now being perfected. The diode with the back-illuminated (from n^+-InP substrate) configuration (BI)[1] has been adopted by most researchers in virtue of some advantages, such as high quantum efficiency, small junction-capacitance, and low dark current. However, the rigid control of epitaxial growth is required because both the quantum efficiency and noise performance of the BI diode which needs more complicated process are closely related to crystallographic perfection in the vicinity of the herojunction interface. On the contrary, the requirement of epitaxial growth of the front-illuminated configuration (FI) diode, in which the process is simpler than that in BI diode, is moderate owing to the fact that the optical-absorption region is allowed to be far from the herojunction interface. Nevertheless, the quantum efficiency, optical pulse response, and dark current of the FI diode may be worse than those of the BI diode due to the carrier diffusion effect resulted from P^+-ν junction-depth, and the photosensitive surface damage in processing. Therefore it is difficult to comment on the two types of diodes up to date.

It has been exhibited by the author's work on the FI diode that the above-mentioned disadvantages can be overcomed by reasonable design of diode parameters as well as the use of some special technological measures, and that the experimental diodes with excellent performance, comparable to the BI diode, are obtained.

Design

At present technological level, the net carrier concentration of LPE $In_{0.53}Ga_{0.47}As$ layer is about 2-8 $\times 10^{15}/cm^3$ although the wafers of $\sim 10^{14}/cm^3$ were also obtained in our institute. If the designed diode is operated under punch-through condition, the i-layer thickness should be extraordinary thin at those doping levels. However the essential ternary-layer thickness, depending on the optical-absorption-coefficient, is required for full absorption of injected photons. This thickness can be calculated from the optical absorption spetra measured (Fig. 1)[2] and is considerably larger than that needed under punch-through condition. Therefore most

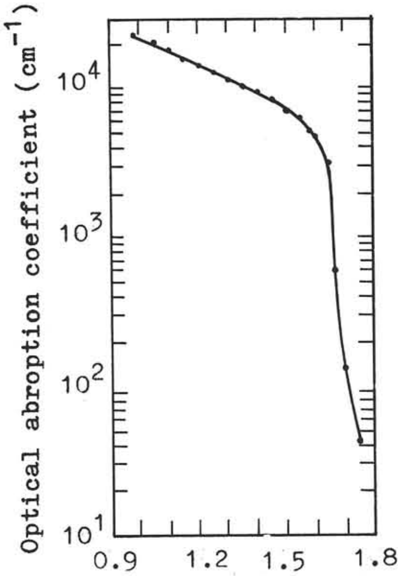

Fig. 1 Optical absorption spectra of $In_{0.53}Ga_{0.47}As$

of practical diodes will be operated under non-punch-through condition.

For the non-punch-through type PIN photodiode shown in Fig. 2, we have deduced from the single-abrupt-junction approximation that the total quantum

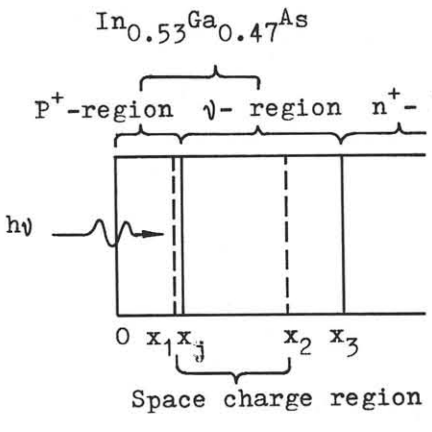

Fig. 2 Sketch of the non-punch-through type PIN photodiode

efficiency η , the dark current density J_D, and the transit-time of photo-excited carrier of the diode $\Delta\tau$ are

$$\eta(\lambda) \approx [1-\gamma(\lambda)]\left\{\frac{1}{\alpha(\lambda)L_n-1}\left[\alpha(\lambda)L_n e^{-X_j/L_n} - e^{-\alpha(\lambda)X_j}\right] - \frac{1}{\alpha(\lambda)L_p+1} e^{-\alpha(\lambda)X_2}\right\} \quad (1)$$

$$J_D \approx q\left\{n_i^2\left(\sqrt{\frac{D_n}{\tau_n}}\cdot\frac{1}{N_A}+\sqrt{\frac{D_p}{\tau_p}}\cdot\frac{1}{N_D}\right)+\frac{n_i(X_2-X_j)}{\tau_e} + A N_D^2 (X_2-X_j)^3 e^{-B/[N_D(X_2-X_j)]}\right\} \quad (2)$$

$$\Delta\tau \approx \frac{qX_j^2}{\mu_n kT} + \frac{X_2-X_j}{v_s} \quad (3)$$

where $\alpha(\lambda)$, $\gamma(\lambda)$ are absorption coefficient and surface-reflection coefficient of $In_{0.53}Ga_{0.47}As$, respectively, Ln, Lp, Dn, Dp, τ_n, τ_p, are diffusion length, diffusion coefficient, and life-time of minority carriers in P^+ and i-regions, correspondly. N_A, N_D are net accepter and donor densities of P^+- and i-regions, and n_i represent intrinsic carrier density of the ternary material. X_j, X_2, X_3 are the positions of $P^+-\nu$ (i) junction-depth, depletion region boundary, and i-layer boundary. τ_e is the effective-carrier-lifetime and μ_n, the electron saturated mobility. v_s equals electron saturated drift velocity in depletion region. A, B are both constants relevant to the fundamental constants of the ternary material. Obviously, if $X_2 = X_j + W$, W is the depletion region width and given by

$$W = \sqrt{\frac{2\epsilon\epsilon_0}{qN_D}(V_R+V_{bi})} \quad (4)$$

where V_R is reverse bias voltage, Vbi and $\epsilon\epsilon_0$ are the built-in potential and permittivity of the ternary material, respectively.

It is shown from digital calculation of (1) - (4) that the junction-depth X_j has an essential effect on η and $\Delta\tau$ of the FI diode in comparison with W. It is also confirmed from the calculated curves in Fig. 3 which gives η and $\Delta\tau$ vs. W, and the spectral-response dependence of the diode with various junction-depthes. Besides the request for high-purity of

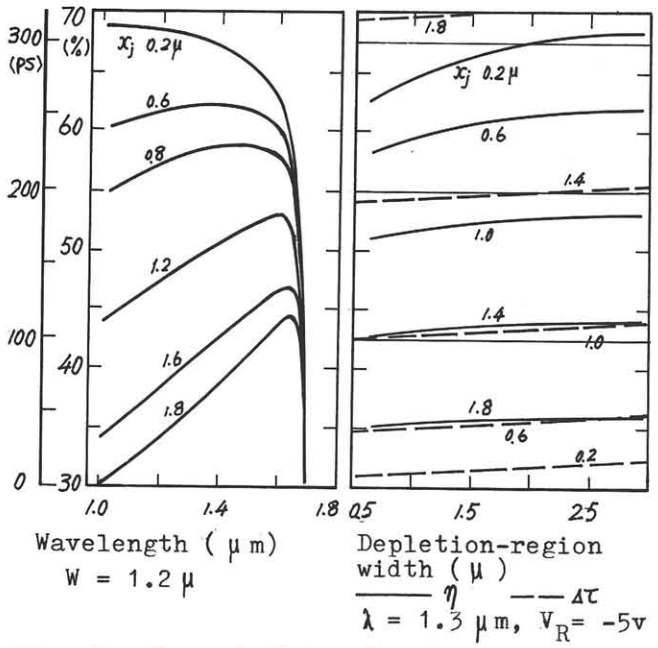

Fig. 3 η and Δτ vs. W as well as spetral-response dependence with various junction-depthes

the i-layer it is necessary for a fine FI InGaAs photodiode to structure technologically a high-doping $P^+-\nu$ shallow junction and the depletion region front while in operation should be as close as possible to the thickness of effective photon-absorption but avoidance of the appearance of notable trnneling current, so that the circuit RC-time constant is ensured to be less than the transit-time $\Delta\tau$. Thus the value of the diode junction-capacitance, Cj,can be determined. In addition, in the derivation of (1) - (3) the effect of the existing surface recombination rate[3] was not involved for its value is dominantly depended on the technological level, hence the high recombination layer on the P^+-surface has to be eliminated during diode preparation.

Preparation

LPE wafers of $In_{0.53}Ga_{0.47}As$ grown on the S-doped InP substrate are used for the FI diodes. The doping range of ternary material is from $1\text{-}8 \times 10^{15}/cm^3$ with electron mobility of more than $7000 cm^2/v \cdot sec$ at room temperature. The thickness of the epitaxial layer is 5 - 8 μ.

The $P^+-\nu$ junction is prepared by simple diffusion of Zn at low temperature (500°C). Two methods are chosen for the P^+ region ohmic contact to save the chip as well as the photosensitive surface from any technological contamination and damage. One is the positive-photoresist off-lift technique. The other is the selected pulse-plating technique with which the metal layer needed for the P^+-ohmic contact and wire-bonding is directly formed on determined area of the mesa. The high yield of 90% of bonded diodes has been obtained by thickening the wire bonding dot (via plating) and low temperature chip dicing. The junction-depth can be controlled repeatedly about 0.5 μ by a special measure with which the high-recombination layer resulted from diffusion process is removed and junction-depth is corrected under monitoring the mesa's responsibility. This method has eliminated the main shortcoming of the FI diode, i.e. the photogenerated-carriers are not fully ultilized, and resulted in high quantum efficiency and rapid pulse response. Fig. 4 shows the SEM photo of the diode mesa.

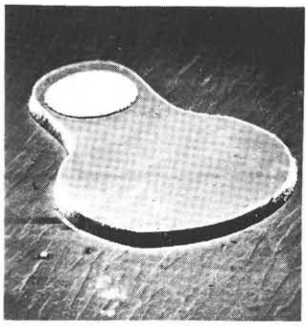

Fig. 4 SEM photo of the diode mesa

Result

The breakdown voltage of the developed diode is larger than 40v (the highest 110v at 10μA).The dark current is usually ≤ 3nA (at 20°C) with the lowest of 0.4nA (corresponding to $J_D = 3.5 \times 10^{-6} A/cm^2$) at -10v bias. The average quantum efficiency of the diode coupled with fiber is ≥ 70% at 1.3μm and

85%, the highest. Normally, the pulse response time measured is ≤ 150 ps and the best, ≤ 100 pf. The total capacitance of the diode is about 0.7pf at -10v bias.

The typical dark current characteristic, capacitance-voltage dependence, spectral response, and pulse-response photograph are shown in Fig. 5-8, respectively.

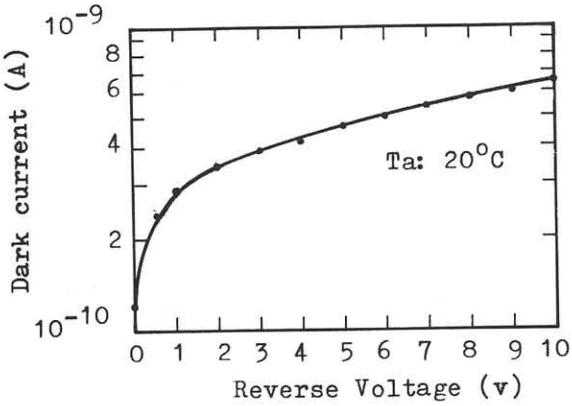

Fig. 5 Dark current versus reverse voltage

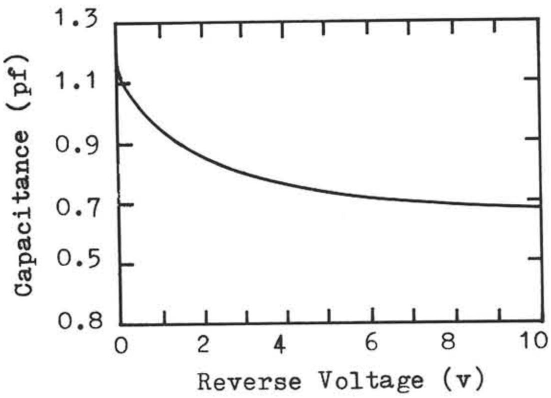

Fig. 6 Capacitance-voltage characteristic

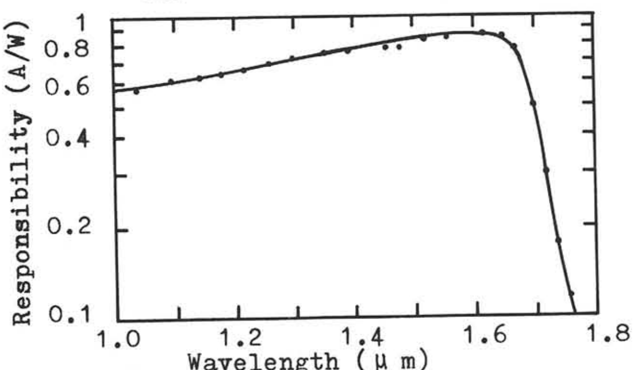

Fig. 7 Spectral-response

Fig. 9 gives the histograph of 84 diodes fabricated on the same wafer. As for the

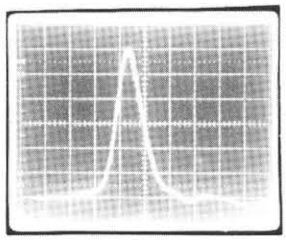

Fig. 8 Pulse-response of a typical diode at -27v bias. 100ps/div.

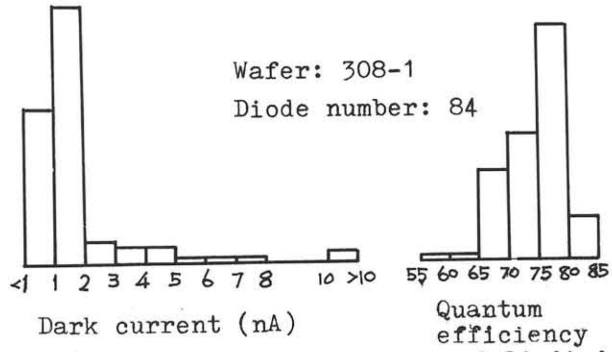

Fig. 9 Performance histogram of 84 diodes fabricated on the same wafer

reliability, the uncapsulated diode mesas after passivation have endured under the strict condition (relative humidity of 95% at temperature alternating in the range of 40°-65°C) for 1000h without notable performance degradation.

Conclusion

As a result of reasonable design of parameters and precise technological control, the $In_{0.53}Ga_{0.47}As/InP$ PIN photodiode with excellent performance has been obtained by means of the front-illuminated configuration, so the severe requirement for epitaxial growth of the ternary material is relaxed.

Reference

1) T.P. Lee, C.A. Burrus et al., IEEE J. Quantum Electronics, QE-17 (1981)232

2) Wang Kai-yuan, Chen Xiao-jian, J. Nanjing Inst. of Tech., 1(1984)102

3) Shiro Sakai, Masayoshi Umeno et al., Trans. Inst. Electron & Commun. Eng. Jpn., J62-C (1979)676