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Narrowband Self-Filtering Photodetector by LPE Growth

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The absorption coefficient in semiconductors varies with photon wavelength and doping concentration. Therefore by suitable control of the depth of the p-n junction and the impurity concentration, together with the limitation of the energy gap, narrowband self-filtering optical detectors can be made. We have used the liquid--phase-epitaxy (LPE) technique to grow the described photodetector with appropriate concentration and thickness. Compared to the original Prince's method of lapping the substrate to the required thickness and using back-illumination, this method is simpler in fabrication and packaging. The spectral response of the fabricated device has a half-bandwidth around 20 nm and a peak value around 880 nm which is adjustable by the grown structure. The result is also close to our theoretical prediction.

INTRODUCTION

When a photodetector is used, because of various extraneous background lights, a matching optical filter is usually placed in front of the detector to optimize its signal-to-noise ratio. However, an external filter causes some reflection loss at the additional surfaces and also increases the packaged volume and labor. It is therefore worthy to have the detector and filter integrated on the same subjstrate. Optical interference filtering by glass coating may be applied to the device, if a flat device surface and accurate control of the coating thickness are obtainable. M.B. Prince' used the wavelength selectivity of a semiconductor material itself to achieve a narrow band self-filtering (NBSF) effect in a GaAs phtodetector. His method (Fig. la) requires lapping and polishing the substrate to a suitable thickness and operating the detector with back-illumination.

We present here a method employing the liquid-phase-epitaxy technique to fabricate the NBSF GaAs phtodiode, with a layer of designated concentration and thickness, on the upper side of the diode junction (Fig. lb). The fabricated device can then perform the NBSF photodetection by conventional front illumination. The advantages of this method are discussed herein.

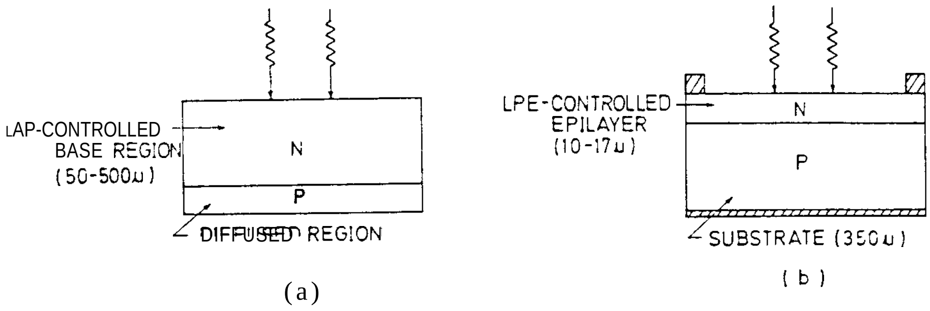

FIG. 1 The structures of narrow-band self-filtering photodiodes. a) M.B. Prince's method' with back-illumination, base region is lapped to a proper thickness; b) Our LPE method with front-illumination

PRINCIPLE OF NBSF PHOTO-DETECTION

As shown in Fig. 1, a photodiode responds to the light reaching the depletion region and the nearby diffusion areas of the p-n junction. As Fig. 2 also shows,[2,3,4] the abosorption of light by a semiconductor strongly depends on the light wavelength and the doping concentration of the materials, Hence short-wavelength lights are strongly absorbed before the active region, while long-wavelength lights are inefficiently absorbed at the region. When photon energies are less than that of the energy gap, no photoelectric response will even occur. Hence by proper choice of the junction depth and the concentrations, a photodiode can respond only to a designated band of wavelength.

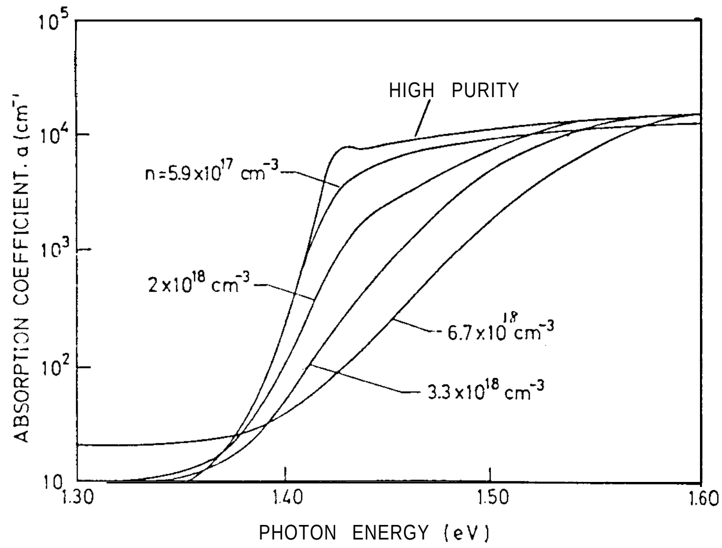

FIG. 2 The variation of absorption coefficient with respect to wavelength and the concentration in n-type GaAs. (from ref. 2,3,4)

As shown in Fig. 3, for commercially available GaAs wafers of doping $>10^{16}/cm^3$, the depletion width, W, is much smaller than the diffusion lengths, L_n and L_p, on both sides of the junction. Hence in the derivation of photoelectric response, the contribution from

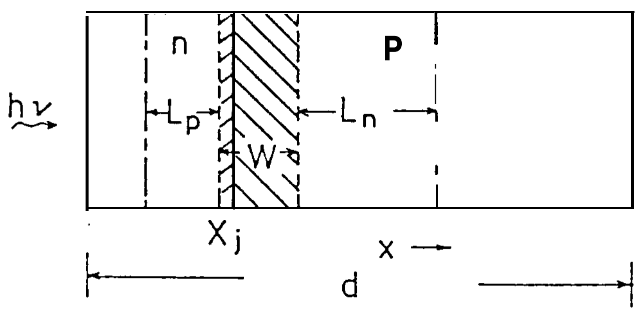

FIG. 3 Geometry of our LPE photodetector.

the space-charge region is negligible, the internal quantum efficiency, Q, of a junction with short-circuit operation can be derived as[1]

$$Q = Q_n \text{ (from n-diffusion region)} + Q_p \text{ (from p-diffusion region)}$$

$$Q_n = b_p \left[\frac{\exp(-b_p y_p)}{b_p + 1} + \frac{\exp\{(1-b_p)y_p\} - b_p + a_p\{\exp((1-b_p)y_p)-1\}}{\{(b_p^2 - 1)\cosh(y_p) + a_p \sinh(y_p)\}} \right]$$

$$Q_p = b_n \left[\frac{\exp(-b_n y_n)}{b_n + 1} + \frac{\exp(-b_n y_n)\exp\{-(1-b_n)(z-y_n)\} - b_n + a_n\{\exp\{-(1-b_n)(z-y_n)-1\}}{(b_n^2 - 1)\{\cosh(z-y_n) - a_n \sinh(z-y_n)\}} \right]$$

Where the normalization factors are

$$y_n = \frac{x_i}{L_n} ; \quad z = \frac{d}{D_n} ; \quad b_n = \alpha(\lambda) L_n ; \quad a_n = \frac{S_n L_n}{D_n}$$

and α is the absorption coefficient, d the thickness of the device, S_n the surface recombination speed, L_n and L_p the minority carrier diffusion lengths on n- and p-side respectively, D_n and D_p the diffusion coefficients.

Fig. 4 shows a simulated example of the response. curve. while Fig. 5 shows the variation of peak wavelength and internal quantum efficiency with the epitaxial thickness.

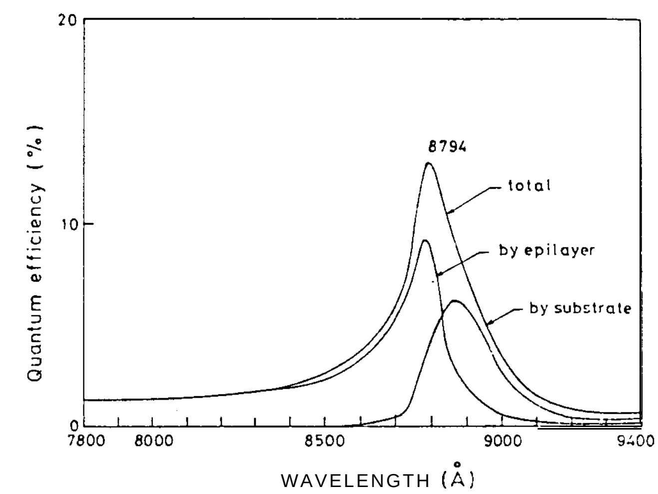

FIG. 4 A simulated response curve.

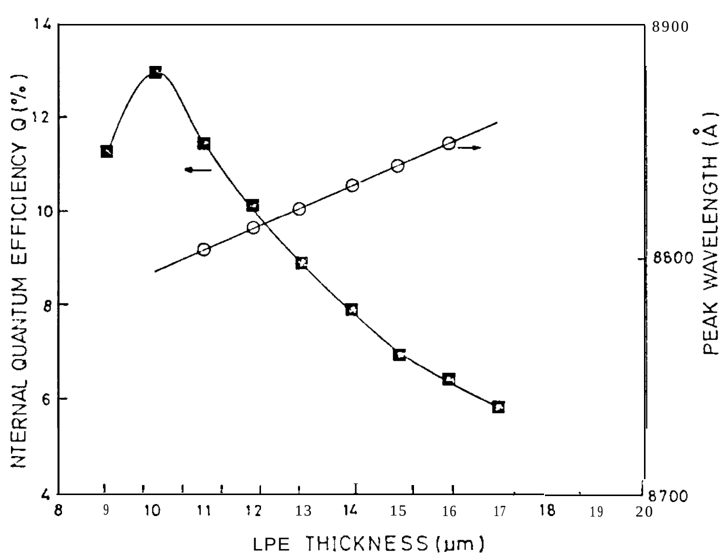

FIG. 5 Theoretical calcualtion of the thickness effect on the peak wavelength and the internal quantum efficiency.

EXPERIMENTS

A conventional LPE system is used to grow a Sn-doped n^+ layer on a p-type ($\sim 10^{18}$ cm^3) GaAs substrate, with a growth rate of $1\mu m$ per 6 minutes at 800 °C. Heavily doped n-layer is formed on the top because the hole has a smaller diffusion length. Hence the effect of blud-side filtering can be made with a thinner epi-layer, which would otherwise impede the red-side transmission and the peak response of the detector. Fig. 6 shows the cross-sections of the grown LPE layer with good thickness uniformity and is close to our prediction.

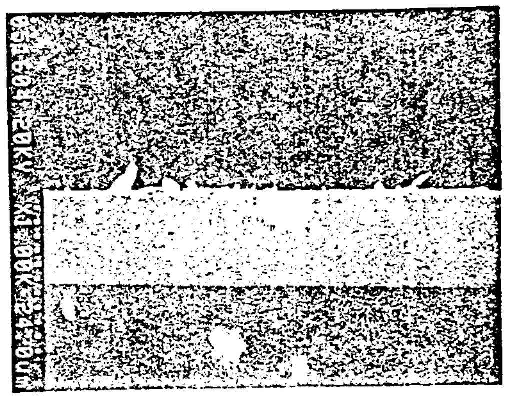

FIG. 6 SEM photograph of the grown LPE layer.

On the grown substrates, p-n junction devices of 5 x 5 mm^2 are fabricated with mesa structure. Ohmic contacts are formed on the back surface with 1% Zn-Au alloy, and on the rim of the front with 12% Ge-Au alloy. Annealing is required to improve the ohmic contact and the diode characteristics.

RESULTS AND DISCUSSION

The spectral responses of the fabricated photodiodes were measured as shown in Fig. 7. By comparing Fig. 4 and Fig. 7, the experiment and the theoretical calculation are in close agreement.

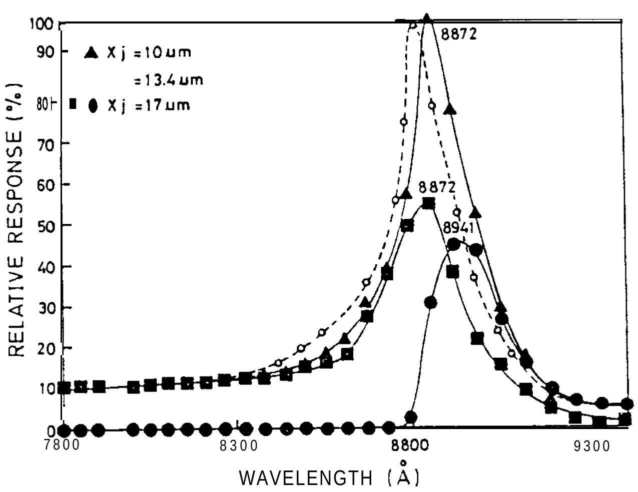

FIG. 7 Experimental spectral response of fabricated photodiodes. Note that sample of $x_j = 10 \mu m$ is in good agreement to the prediction (blank circle) of Fig. 4.

. The incomplete supression of the blue-side wavelength is due to the photon re-emission in the high concentration epi-layer.[5] Lowering the concentration at the upper layer could improve the effect, as indicated by Fig. 2. But this also increases the minority-carrier diffusion length thus breaking even the blue-side filtering.

The quantum efficiency is close to that obtained by Prince's method. Its low value is caused by the thin active layer, which is mainly the minority carrier diffusion length at the substrate concentration. Lowering the substrate concentration will enlarge the depletion thickness, and improve the quantum efficiency in the preferred long-wavelength side due to the moving down of the depletion region. This effect is also opposite to Prince's back-illumination structure.

Our LPE method can further improve the NBSF diode performance by a proposed structure as shown in Fig. 8. A hi-lo-hi epi-layer on a low doping or semi-insulation substrate. The blue-side suppression is mainly performed by the low-concentration middle epi-layer with controlled thickness. This is because of its higher absorption constant (Fig. 2),

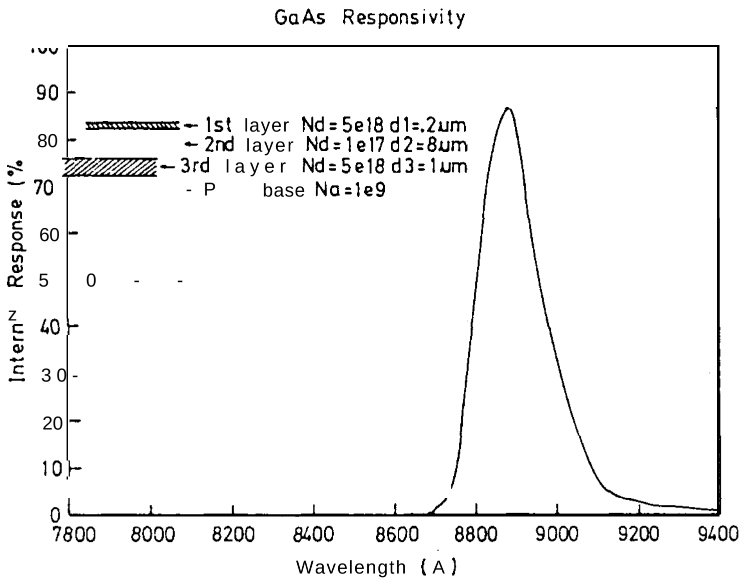

FIG. 8 a) A proposed NBSF photodiode with hi-lo-hi structure; b) One of the simulated response curves of the structure with excellent filtering and peak quantum efficiency.

and low re-emission at the shorter wavelengths. While the upper high concentration epi-layer is for ohmic contact, the lower high concentration layer is for reducing the diffusion length and the depletion edge from reaching the middle of the low concentration region. Fig. 8b shows the much improved quantum efficiency with a value of 87% in one of our theoretical simulations.

CONCLUSIONS

The fabrication and performance of a NBSF photodiode can be simpler and better, if the LPE technique is used to grow a structure with proper thickness and concentration. Our method can also produce a hi-lo-hi epitaxial structure, which will greatly enhance the blue-side suppression quality as well as the peak quantum efficiency. This special structure is currently under investigation in our laboratory.

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