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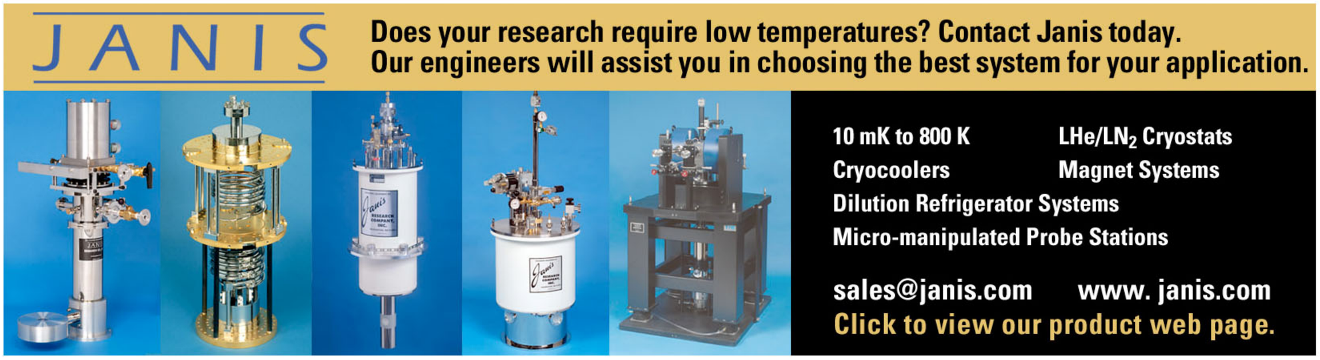

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REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 113108 (2005)

Fabrication of narrow-band self-filtering GaAs photodetector by epitaxy

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A narrow-band self-filtering (NBSF) GaAs photodiode has been fabricated by the LPE technique, where epilayers of high-low-high N doping were grown on a P-type substrate. By proper control of the thickness and doping concentration of each layer, it can be demonstrated that the fabricated NBSF detector has a spectral bandwidth as narrow as 315 Å at 880 nm peak wavelength. This means over 98% of the blue-side light is suppressible, indicating that the NBSF photodetector is a useful device for many applications where the suppression of high background light is necessary. © *2005 American Institute of Physics.* [DOI: 10.1063/1.2133996]

I. INTRODUCTION

The consumer electronic industry nowadays demands a huge quantity of optoelectronic devices. A major portion of that is categorized into applications in infrared (IR), free-space data communications, such as infrared data acquisition (IrDA),[1] remote control of home appliances, etc. In such kinds of applications, a pair of optical transmitters and receivers is required in order to transmit light data between two line-of-sight locations. A matching filter is generally required to place in front of a photodetector in order to suppress various extraneous background illuminations; therefore preventing the detection signal from saturation as well as reducing the background noise to improve the signal-to-noise ratio thereafter.[2] However, an external filter causes extra reflection loss at two air-filter interfaces and increases the cost and device volume, which are not favorable for designing compact electronic products. For example, an IrDA device used in a mobile phone should be extremely small in dimension and has a strong ability for preventing background light from saturation.

One better way to reduce the size can be achieved by building an efficient narrow-band optical filter onto the surface of the photodetector. This optical filter can be made by applying the technique of multilayer coating on the surface of the detector wafer having a designated spectrum matching to the light emitter wavelength. However, the multilayer optical coating is not the standard process in current semiconductor foundries and finding one to fabricate the narrow-band filter is not only difficult but also highly expensive. Another way to achieve the background suppression is by mixing a spectral dye as an additive in a molding compound, so that after encapsulating the detector, the compound plays as an absorptive filter to background light as well. Today this compound is widely used, but only long-pass types having cut wavelengths around an 800 nm range are available in the industry; dye materials having specific narrow-band spectra are hard to find.

In this paper, an effective method of making a photodiode with a narrow-band response is presented. The diode performs absorption filtering through its own substrate and the shortcomings mentioned above can be solved. Prince[3] had been able to demonstrate such a narrow-band self-filtering (NBSF) GaAs photodetector using the device substrate as the absorbent, as shown in Fig. 1(a). The photodetector was made to operate with a back-illumination scheme, where incident photons with a wavelength shorter than that of the energy-gap cutoff are absorbed in the substrate before reaching the junction in the deep bottom. However, this device structure presents certain degrees of difficulty in fabrication and performance. First, in order to control the accuracy of spectral absorption, tedious lapping and polishing of the GaAs substrate to a suitable thickness must be required, as the substrate concentration strongly determines the absorption strength. Second, the process for patterning the backside electrode with a window open to allow light entering properly on the active area is rather difficult without a double-sided aligner for lithography. Finally, the back-illumination scheme needs more skill and cost to do package of the device chip.

In this paper, we describe an improved structure to overcome all these problems. The improved structure is shown in Fig. 1(b), which employs an epitaxial technique to make an excellent NBSF detector of front illumination.

II. EPITAXIAL NBSF DETECTOR

A photodiode responds functionally to light that reaches its depletion and the diffusion regions. Owing to the energy gap property of semiconductor materials, light with wavelengths far shorter than the cutoff wavelength of an energy gap undergoes strong absorption, hence reaching only to a shallower depth.[4] The sensitivity of a detector to such light is much less for a deep junction below the light-facing surface. On the other hand, the photosensitivity drops drastically and finally ceases when the light wavelengths are over the absorption edge. As a result, all semiconductor photodetectors show bandlike spectral responses, with peak wavelengths closely pinned to the individual cutoff wavelengths. Hence, it is understandable that the shape of the spectral response of a

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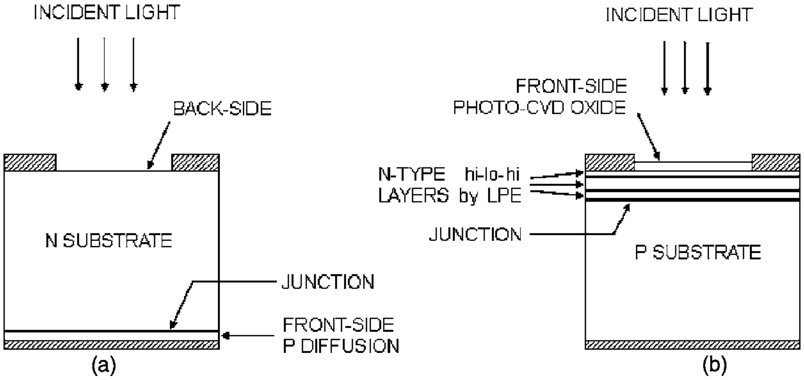

FIG. 1. Structures of narrow-band self-filtering photodiodes: (a) back-illumination scheme; Ref. 3; (b) the present front illumination scheme grown by the LPE method, with the following conditions: P substrate at $10^{18}/\mathrm{cm}^3$ (Zn doped) and 300 μm thickness; first N-type epilayer at $8\times 10^{18}/\mathrm{cm}^3$ and 1 μm; second N layer at $5\times 10^{16}/\mathrm{cm}^3$ and 8 μm; third N layer at $8\times 10^{18}/\mathrm{cm}^3$ and 0.5 μm.

photodiode is an expression of its junction structure, which is mainly characterized by the junction depth and the depletion width. In direct energy-gap materials, such as GaAs, the absorption varies sharply at the cutoff edge.[4] As a result, high-performance NBSF photodiodes can be made by careful design of the junction structure.

In this study, the authors discover that the property of concentration dependency of optical absorption in semiconductor materials is useful knowledge for making good NBSF detectors. As shown in Fig. 2, the absorption coefficient in the GaAs material depends significantly on its doping concentration and the type of dopant.[5–7] This was not noted before, to the best of our knowledge.[3] One notes that the absorption coefficient is eminently lower for high-doping materials, especially to N-type material. The mechanism that causes the low absorption is attributed to the Burstein–Moss effect of photon reemission.[8] Based on the information, low doping GaAs material has the ability to absorb short-wavelength light thoroughly in the few micrometer range. Practically, such a thickness allows us to grow the absorption layer on GaAs substrates by convenient epitaxial techniques, such as metal-organic chemical vapor deposition (MOCVD) or liquid phase epitaxy (LPE).

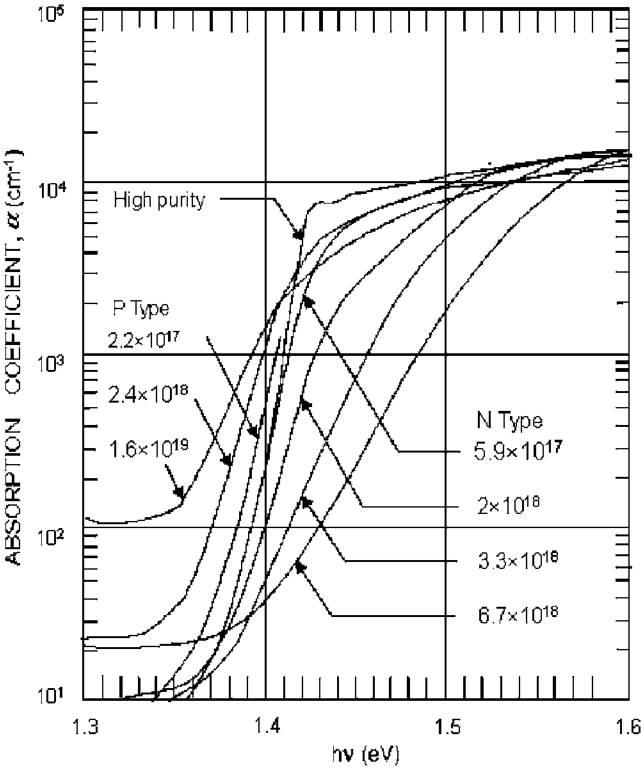

FIG. 2. The wavelength variation of the absorption coefficient on doping concentration of GaAs material. The curves are replotted from the data obtained by Casey (Ref. 7).

As shown in Fig. 1(b), a photodiode responds to the incident light in three regions: the depletion region of the junction and the nearby minority-carrier diffusion regions on either side of the junction. The upper diffusion region is close to the light incidence surface; hence it responds to the blue wavelength of the high absorption coefficient and needs to be minimized. On the contrary, the lower thus deeper diffusion region responds to the red wavelength of low absorption and should be maximized to gain more sensitivity. In GaAs material, the electron has a much larger mobility ($\sim$8500 $\mathrm{cm}^2/\mathrm{V\,s}$) and a diffusion length compared to that of hole ($\sim$400 $\mathrm{cm}^2/\mathrm{V\,s}$).[9] Therefore the P substrate is preferred, as it will provide a larger diffusion length below the junction, where the electron is the minority carrier. Under such conditions, the top layer has to be N type, which happens to have a smaller hole diffusion length to reduce the blue response. This choice of substrate type is contrary to the N wafer used in the previous reports.[3]

Accordingly, an improved NBSF GaAs photodiode is proposed as shown in Fig. 1(b), where a three-layer structure of N-type high-low-high doping is epitaxial grown on a P substrate. The first highly doping N epilayer is for N–P junction formation. The photoactive diffusion length in the epilayer is depressed by its heavily N-type doping, which further drops the hole mobility down below 100 $\mathrm{cm}^2/\mathrm{V\,s}$ at a $10^{19}/\mathrm{cm}^3$ concentration.[10] This is equivalent to a diffusion length shorter than 0.5 μm if the lifetime is 1 ns. The subsequent second N layer is to allow efficient light absorption and must be thick and lightly doped, according to Casey's empirical data of Fig. 2.[7] The third highly doping N layer is used purely for ohmic contact with a minimum epithickness. By this epitaxial structure, the device can be fabricated and operated with front illumination like a conventional photodiode, as discussed below.

As indicated in Fig. 2, N-type doping concentrations lower than $5\times 10^{17}/\mathrm{cm}^3$ have an absorption length of just over 1 μm at the cutoff wavelength of $\sim$880 nm. This means that over 99% of incident light on the blue side of the peak wavelength will be absorbed within a 5 μm thickness.

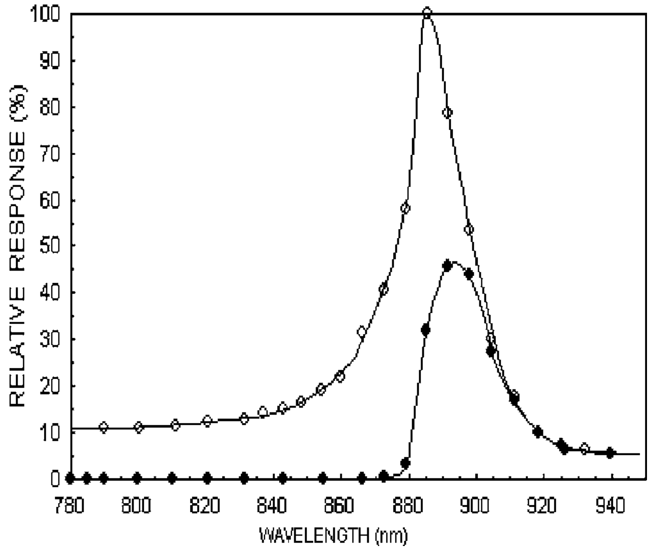

FIG. 3. The spectral response of NBSF detectors with a single absorption layer of heavy *N* dopant (Ref. 8). Notice that the incompleteness of blue suppression in the sample of a thinner epitaxy of 10 μm (open dots ○); and the degradation in the sensitivity of a thicker sample of 17 μm (solid dots ●).

In our previous study[9] this second layer of low doping was omitted, and incomplete blue suppression for insufficient thickness of absorption was observed, as indicated by open dots (○) in Fig. 3. Contrarily, if the epithickness is over, the peak response is degraded, as shown by solid dots (●). These effects lead to a tradeoff in the difficulty of making a good NBSF detector by single absorbing the *N* layer. It justifies the necessity of introducing the high purity second layer, as proposed in this work. Careful control of the growth conditions, both thickness and purity, are important. In reference to Fig. 2, a purity of less than $10^{17}/\mathrm{cm}^3$ is most preferred.

Based on the above concept, we performed the numerical computations to obtain the optimal concentration and thickness of each epitaxial layer for experiment, as listed in Fig. 1(b). In the numerical analysis, we have also found that the response spectrum is tuned slightly by the substrate concentration. This indicates the stability of the peak wavelength of the NBSF photodetector, regardless of the substrate condition.

III. EXPERIMENT

According to the simulation result, an NBSF GaAs photodiode is fabricated by the conventional low-cost LPE technique, despite the fact that the more expensive MOCVD method is desirable. The *P* substrate is Zn doped at the designated concentration. A gradual cooling technique[11] is adopted in the LPE process with a cooling rate of $0.2\,^{\circ}\mathrm{C/min}$ down from 880°. The Te dopant at $8 \times 10^{18}/\mathrm{cm}^3$ is used to grow the first layer of 1 μm thickness for the *N*–*P* junction formation. Subsequently, the second layer of 8 μm thickness is grown doped with Sn at the listed concentration. Finally, a 0.5 μm top layer is grown with the same concentration as the initial layer.

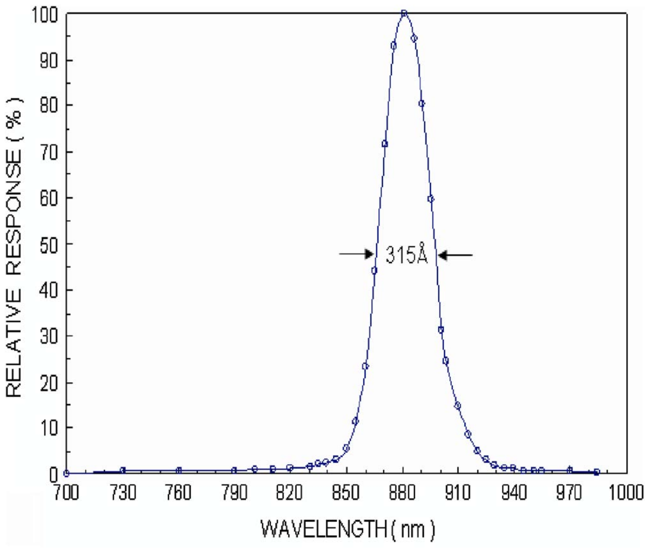

FIG. 4. The relative spectral response of the fabricated GaAs NBSF photodetector. Three samples chosen from a batch of chips were packaged and measured, all with closed agreement.

After LPE growth, the wafer is further processed for photodiode fabrication. A Au–Ge alloy is adopted for the top ohmic contact on the edge of the active area. A low-temperature photo-CVD[12] is applied on the device surface to form a quarter-wavelength thin oxide of 150 nm, serving the purposes of surface passivation as well as reducing reflection loss.

IV. RESULTS AND DISCUSSIONS

One packaged sample of good electrical characteristics, which are mainly related to dark current and breakdown voltage, was chosen from a batch of the fabricated devices for optical testing. The device is measured under a short circuit condition at zero bias. Figure 4 shows the relative spectral response measured. A full width at half maximum (FWHM) as narrow as 315 at 880 nm peak wavelength has been achieved.

We think the measured data is trustable; not only the device is measured by equipment in the ITRI laboratory, which has ISO approved standards within 5% error, but also because the devices that have no absorptive second layer with characteristics as shown by the curves in Fig. 3 were also measured together for reference. One should notice that, except for the baseline, all curves show only a slight difference within 5 nm, both in the bandwidth and peak wavelength. The comparison also justifies our theoretical expectation. The estimated absolute quantum efficiency is over 40% at the peak response. As shown in Fig. 4, the blue-side suppression is not complete in our experimental samples as about 2% of the transmission leak remained. Presumably, this is caused by the impurity diffusion across the layers during the high-temperature processing of LPE. It is expected that, despite a higher cost, the MOCVD technique could provide a better result because of its low-temperature reaction.

As is well known, a semiconductor substrate with higher purity can provide a longer lifetime, or diffusion length.

Therefore, the purest P substrate available is most preferred for the epitaxial base, which will give the widest depletion and diffusion thickness below the junction. Unfortunately, our experiment had a substrate concentration at $10^{18}/\text{cm}^3$ high. In future studies, the purity can be improved by initially growing the purest P layer before the first N layer. However, it is known that growing a concentration lower than $10^{16}/\text{cm}^3$ by the LPE technique is difficult today, and, again, MOCVD is a better solution in this aspect.

According to our calculation, the NBSF detector made by this experiment can provide nearly 30 dB power attenuation on an incident solar background, based on the response spectrum obtained and that of a 6000 K blackbody.[13] This excellent background screening ability indicates that the fabricated device is very useful for various purposes of near-infrared communications in free space having a strong light environment. In addition, owing to the nature of short recombination time of the GaAs material, the fabricated photodiode is also gifted with high speed.

V. CONCLUSIONS

In this paper we have shown that a narrow-band self-filtering photodiode can be fabricated utilizing a liquid-phase-epitaxy substrate grown on a GaAs wafer. This detector introduces a low doping N-epitaxial layer as the absorption filter to suppress the unwanted strong background light, thus enhancing the dynamic range of the detector. By this epitaxy structure, the detector can be operated with front illumination, therefore lowering the cost of fabrication and package.

The theory of this study also indicates that, by using the modern epitaxial techniques and the present design concept of energy-gap engineering, it is possible to extend the concept to fabricate similar NBSF photodiodes at different wavelengths, which are achievable by III-V semiconductor systems having a direct energy gap.

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