AN AlGaAs-GaAs DUAL-WAVELENGTH PHOTO-DETECTOR WITH 500 Å RESOLUTION

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(Received 23 January 1984)

Abstract—An Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs Schottky barrier dual-wavelength photodetector with 500 Å resolution has been developed. By varying the reverse bias, the phototreshold of the detector can be changed from 0.82 to 0.87 μm. The diode can thus be applied to demultiplex two optical signals with respective wavelengths of 0.8 and 0.85 μm. This provides a useful detector for use in a dual-channel optical communication system. The principle is based on the band readjustment effect which is due to the interaction of the closely-spaced Au-AlGaAs Schottky barrier and the AlGaAs-GaAs heterojunction.

1. INTRODUCTION

Wavelength-division-multiplexing (WDM)[1] is a technique widely used in fiber optic communications for transmitting a number of signals simultaneously through a single fiber at different wavelengths. This technique increases the information-carrying capacity of the fiber, and provides flexibility in fiber-network design. In a WDM system, a multiplexer and a demultiplexer are necessary for the transmitter and receiver, respectively. Current approaches[2-6] to optical demultiplexing circuits consist of optical components, such as diffraction gratings, prisms and thin film filters, and dual wavelength InGaAsP/InP photodiodes[7]. Designs using optical components must include collimating or focusing optics and are sensitive to the alignment with the optical fibers. The dual-wavelength InGaAsP/InP photodiode developed by Campbell *et al.* [7] can demultiplex two signals at 1.08 and 1.18 μm. In this paper, we describe a dual-wavelength photodiode with simple structure, namely an Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs Schottky barrier diode, which can demultiplex two signals in the 0.8-0.85 μm region (500 Å resolution).

2. OPERATION PRINCIPLE

The structure of a Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs dual-wavelength photodetector is shown in the insert of Fig. 1. The operation principle involved, as illustrated in Fig. 1, is the band-readjustment effect[8] which is due to the interaction of two closely spaced junctions, namely the Au-AlGaAs Schottky barrier and the AlGaAs-GaAs heterojunction. Figure 1 displays the valence-band-maximum profiles of this device under different biases which is calculated from the Poisson equation with the following parameters obtained from a fabricated device No. 116: the thickness, bandgap and doping concentration of the AlGaAs layer are 6350 Å, 1.52 eV and $1.4 \times 10^{16} \text{ cm}^{-3}$, respectively, the built in potential of the Au-(N)Al_{0.07}Ga_{0.93}As Schottky barrier is 0.9 V, and the impurity concentration of the GaAs layer is $4.8 \times 10^{14} \text{ cm}^{-3}$. It is clear that, under zero bias, there

is no overlap between the depletion region of the left Au-AlGaAs Schottky barrier and the right AlGaAs-GaAs heterojunction. The AlGaAs layer is defined to be effectively thick [8]. In the valence band, a potential barrier of 0.158 eV appears near the AlGaAs-GaAs heterojunction which prevents the photogenerated holes of the GaAs layer from injecting into the AlGaAs layer. Consider a 0.85 μm optical signal with energy (1.46 eV) between the bandgap energies of GaAs and Al_{0.07}Ga_{0.93}As incident from the Schottky barrier side, the electron-hole pairs will be generated entirely in the GaAs side. They can not be detected under zero bias. As the reverse bias is raised, say to -2.2 V, the Schottky barrier depletion layer extends deeper into the AlGaAs and begins to interact with the right heterojunction depletion layer. Further increasing the reverse bias tends to suppress the built-in potential of the N-n heterojunction and its depletion layer width. When the bias reaches -3.19 V, the heterojunction built-in potential is entirely suppressed and the valence band of the GaAs layer becomes a "flat band". The photo-generated holes in the GaAs layer then start to transport across the heterojunction and be collected. At an even larger reverse bias, i.e. -4 V as shown in Fig. 1, the Schottky barrier penetrates into the GaAs layer and the photocurrent approaches a maximum. Consider two optical signals with respective wavelengths of 0.8 and 0.85 μm incident on the detector, only 0.8 μm signal which is mainly absorbed by the top AlGaAs layer can be detected under zero bias, whereas both signals can be detected under -4 V reverse bias.

3. EXPERIMENT

(N)Al_{0.07}Ga_{0.93}As-(n)GaAs double layers were grown on Si-doped n^+ substrates by LPE techniques. The AlGaAs layer was Sn-doped to a concentration of $1.4 \times 10^{16} \text{ cm}^{-3}$, and the GaAs layer was undoped with a background impurity concentration of $4.8 \times 10^{14} \text{ cm}^{-3}$. A semitransparent Au film was vacuum evaporated on the AlGaAs layer to form the

Fig. 1. The valence-band-maximum profiles of an Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs Schottky barrier diode under different biases: zero, -2, -3.19, and -4 V. The thickness, bandgap and doping concentration of the AlGaAs layer are 6350 Å, 1.52 eV and $1.4 \times 10^{16} \text{ cm}^{-3}$, respectively, the built-in potential of the Au-(N)Al_{0.07}Ga_{0.93}As Schottky barrier is 0.9 V, and the carrier concentration of the GaAs layer is $4.8 \times 10^{14} \text{ cm}^{-3}$. The insert is the structure of this device.

Schottky barrier. The area of each diode is $1.3 \times 10^{-2} \text{ cm}^2$. The spectral responses of the device under different applied voltages were measured by lock-in techniques [8]. The light source was calibrated by a standard solar cell.

4. RESULTS

Figure 2 displays the spectral responses of the double-layer Schottky-barrier photodiode No. 116. The independent parameters are the applied reverse

Fig. 2. Spectral responses of a Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs Schottky barrier device No. 116 under different reverse biases: zero, -2, -4 and -5 V.

Fig. 3. Dark and light I - V plots of sample 116. Light 1 and 2 curves were taken under the illumination of a tungsten lamp and the same lamp plus IR filter, respectively.

voltages. It can be seen from the figure that, at 0 and -2 V, the spectral-response curves have a cutoff at $0.816 \mu\text{m}$ (1.52 eV) which corresponds to a bandgap energy of the Al_{0.07}Ga_{0.93}As layer. At -4 and -5 V, however, not only are the collection efficiencies enhanced, but also the threshold wavelength increases to $0.864 \mu\text{m}$, which corresponds to the bandgap energy of the GaAs layer. The increase in threshold indicates that the Schottky barrier depletion layer has penetrated into the underlying GaAs layer. Figure 3 shows the corresponding dark and light I - V characteristics of the same device. Under the illumination of the light 1 which was simply a tungsten lamp, the I - V curve displays a sudden increase at reverse voltages beyond -3 V. Light 2 was produced by adding an Oriel 5136 filter to the light 1; this filtered out photons with wavelengths shorter than $0.82 \mu\text{m}$. Thus, light 2 could only be absorbed by the GaAs layer. It is evident that the I - V curve under light 2 indicates no photocurrent between 0 and -3 V, whereas the photocurrent begins to flow beyond -3.2 V.

The $1/C^2$ vs V plot of device 116 is shown in Fig. 4. Before the Schottky-barrier depletion region penetrates into the GaAs layer, i.e. reverse bias smaller than -3 V, the $1/C^2$ - V relation gives information about the built-in potential of the Au-(N)Al_{0.07}Ga_{0.93}As layer and the carrier concentration of the AlGaAs layer which are 0.9 V and $1.4 \times 10^{16} \text{ cm}^{-3}$, respectively. However, after the depletion region penetrates into the GaAs layer, one should take both the AlGaAs and GaAs layers into account involving their different doping concentrations and dielectric constants. The $1/C^2$ - V relation can be derived as

$$\frac{1}{C^2} = \frac{2}{q\epsilon_2 N_{d2}} \left(V_{bi1} + V_{bi2} - V_a - \frac{qN_{d1}d^2}{2\epsilon_1} \right)$$

with the condition that the doping concentration of the AlGaAs layer N_{d1} is much larger than that of the GaAs layer N_{d2} . Where V_{bi1} , V_{bi2} and ϵ_1 , ϵ_2 are the respective built in potentials of the Au-AlGaAs

Fig. 4. $1/C^2$ - V plot of sample 116.

Schottky barrier and the AlGaAs-GaAs heterojunction and the dielectric constants of the AlGaAs and GaAs layers. d is the thickness of the AlGaAs layer and V_a is the applied voltage. The relation shows that the extrapolation of the linear part of the $1/C^2$ curves to the voltage axis is the "flat band" voltage which is the required bias that just suppresses the AlGaAs-GaAs heterojunction built-in potential. The slope of the curve is inversely proportional to the doping concentration of the GaAs, not the AlGaAs layer. It is evident from Fig. 4 that, at a reverse voltage beyond -3 V, the $1/C^2$ curve appears to be linear with a carrier concentration of $4.8 \times 10^{14} \text{ cm}^{-3}$ and an intercept of -3.2 V. This indicates the "flat band" voltage is -3.2 V, which is consistent with the results for the spectral responses and the light I - V characteristics.

5. DISCUSSIONS

To apply this photodetector for use in the WDM technology, the traditional demultiplexing circuit[1] must be slightly modified. Its block diagram is shown in Fig. 5. Two modifications have been made: one is the insertion of a fixed gain ($1/f$) proportional amplifier and the other is the replacement of the channel 2 preamp with a differential amplifier. The detector is composed of two adjacent Schottky barriers on a single chip, as shown in the insert of Fig. 1. Detector one is biased at -2 V to detect a fraction of the $0.8 \mu\text{m}$ signal, whereas the detector 2 is biased at -5 V to totally collect both 0.8 and $0.85 \mu\text{m}$ signals. The $0.85 \mu\text{m}$ signal (λ_2) can be separated out from the $0.8 \mu\text{m}$ (λ_1) signal by using a differential amplifier. Since the AlGaAs layer has a finite thickness, only a fraction (f) of the $0.8 \mu\text{m}$ signal can be absorbed in the AlGaAs layer, i.e. $f = 1 - \exp(-\alpha d)$ where α and d are the absorption coefficient and the thickness of the AlGaAs layer. Therefore, a proportional amplifier with a fixed gain of $1/f$ must be inserted before applying the output of the detector

Fig. 5. Demultiplexing circuit for using with the Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs Schottky barrier photodiode.

one to the differential amplifier to eliminate the crosstalk in channel 2. For example, the absorption coefficient α of the Al_{0.07}Ga_{0.93}As ($E_g = 1.52$ eV) at wavelength $0.8 \mu\text{m}$ (1.55 eV) can be assigned to be $9 \times 10^3/\text{cm}$ (9, 10), the factor f becomes 0.42 if we choose d to be $0.6 \mu\text{m}$. It is interesting to note there is also no crosstalk in channel 1 since the Al_{0.07}Ga_{0.93}As layer does not absorb $0.85 \mu\text{m}$ (1.46 eV) signal at all. The crosstalk caused by misalignment between the optical fiber and the photodetectors can be minimized by using interdigit-shaped Schottky-barrier designs. Since the optical power is shared equally by two photodetectors, the insertion loss of this device is 3 dB.

6. SUMMARY

An Au-(N)Al_{0.07}Ga_{0.93}As-(n)GaAs dual wavelength photodiode was shown to be able to demultiplex two optical signals with $500 \text{ \AA}$ resolution, namely 0.8 and $0.85 \mu\text{m}$ respectively. It provides a useful detector for use in a dual-channel optical communication system.

Acknowledgement—This work was supported by National Science Council of Republic of China under grant NSC72-0404-E002-R033.

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