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# Very Wide Spectral Range Schottky Photodiodes of Ag/p-InP/p-InGaAs Heterostructure

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The Schottky photodiodes of Ag/p-InP/p-InGaAs heterostructure are fabricated by LPE growth of p-InGaAs/p-InP/InGaAsP/InP multiple layer heterostructure and its selective etching. The idea is to add the longer wavelength photoresponse of InGaAs to that of InP, and thus to obtain a very wide(0.4 μm∿1.65 μm)spectral range Schottky photodiodes. The wide and a fairly flat spectral response is demonstrated for the Ag/p-InP/p-InGaAs Schottky photodiodes.

## §1. Introduction

Much interest has been focused on the InGaAs(P)/InP heterostructure for its applications to optoelectronic devices such as DH(double heterostructure) lasers and APD's(avalanche photodiodes) in the optical communication system. For these devices, narrower spectral range of the emitted light or photoresponse is required at 1.3 μm or 1.55 μm[1,2]. On the other hand, when the heterostructure is used in such a way as to add the spectral range of each layer, it could be possible to fabricate photodetectors which have a very wide and flat spectral response. In the InGaAs/InP heterostructure the spectral range could be extended from 0.92 μm(corresponds to the energy gap 1.35 eV of InP) to 1.65 μm(corresponds to the energy gap 0.75 eV of $In_{0.53}Ga_{0.47}As$) if the structure is so designed as to add the spectral response of $In_{0.53}Ga_{0.47}As$ to that of InP.

In this paper, we describe the fabrication of Schottky photodiodes of the Ag/p-InP/p-InGaAs heterostructure and demonstrate its very wide and fairly flat spectral response from violet(∿0.4 μm) to infrared(∿1.65 μm).

## §2. Fabrication of Ag/p-InP/p-InGaAs Schottky Diodes

Since the Schottky contact on InGaAs is leaky at room temperature(RT)[3], InP on top of InGaAs was used to obtain a high barrier Schottky contact. To extend the depletion layer of metal/p-InP Schottky contact well into the InGaAs layer, a thin InP layer with a low carrier concentration on top of InGaAs is required. Since it is very difficult to grow InP directly on InGaAs, we fabricated the Schottky diodes of Ag/p-InP/p-InGaAs from the p-InGaAs/p-InP/InGaAsP/InP multiple layer by the selective etching of InGaAsP and InP. The photomicrograph of the cleaved and delineated cross section of the multiple layer is shown in Fig. 1.

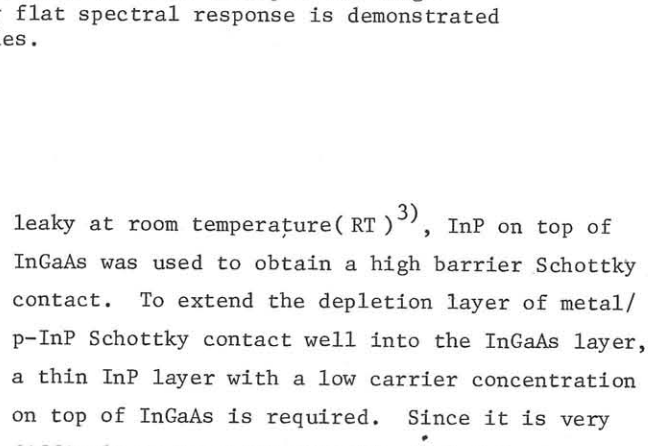


Fig. 1 Cleaved and delineated cross section of InGaAs/InP/InGaAsP/InP multiple layer.

The multiple layer was grown by LPE using a conventional slider and boat assembly in Pd-diffused hydrogen atmosphere. p-InGaAs and p-InP of low carrier concetration($p \lesssim 1\times10^{16}$ $cm^{-3}$) were reproducibly obtained with dopant Zn diluted with In. The InGaAsP quaternary alloy of which composition corresponds to the emission light wavelength 1.3 μm was used as the buffer layer for the selective etching. Typical thicknesses of each layer are 15 μm for p-InGaAs, 0.5 μm for p-InP, and 0.3 μm for InGaAsP. Before the selective etching, the wafer of the multiple layer heterostructure was bonded to the InP wafer by Au-Ge alloy in a nitrogen atmosphere at 400°C. First, InP was etched out in HCl at RT. The etching stops at the InGaAsP layer surface. The quaternary layer was selectively etched using a solution of $H_2SO_4:H_2O:H_2O_2$ (= 1:1:1 in volume) at RT. Since this etching stops at the InP surface, we finally obtain the inverted structure of p-InP/p-InGaAs from the p-InGaAs/p-InP/InGaAsP/InP multi-layered heterostructure. Evaporation of Ag Schottky contacts onto InP completes the fabrication of Ag/p-InP/p-InGaAs Schottky diodes. This final structure is schematically shown in Fig. 2. The InP wafer is the holder of a thin Ag/p-InP/p-InGaAs layer.

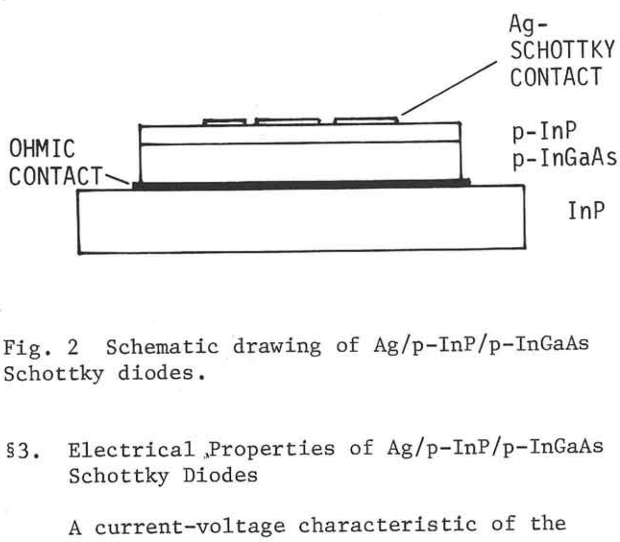


Fig. 2 Schematic drawing of Ag/p-InP/p-InGaAs Schottky diodes.

§3. Electrical Properties of Ag/p-InP/p-InGaAs Schottky Diodes

A current-voltage characteristic of the Schottky diode fabricated in the wafer #107 which has the layer thicknesses of 480 Å for Ag, 0.6 μm for p-InP, and 11 μm for p-InGaAs is shown in Fig. 3. The diameter of the Ag Schottky contact is 0.9 mm. The built-in voltage in the forward direction is low although the Schottky barrier height is as high as 0.8 eV. The Schottky barrier height was measured from the photon energy dependence of the Ag/p-InP Schottky diodes where the electrons are injected from the metal contact to p-InP by the photo-excitation. Even though the built-in voltage is low, the leakage current in the backward direction is very low as can be seen in Fig. 3, and breaks down at a voltage as high as − 15 V.

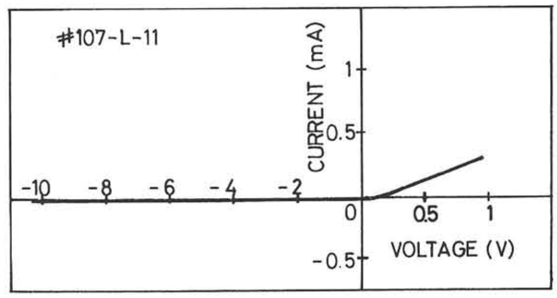


Fig. 3 Current-voltage characteristic of Ag/p-InP/p-InGaAs Schottky diode of size φ=0.9 mm measured at RT.

A capacitance-voltage( C-V ) characteristic of the same wafer as in Fig. 3 is shown in Fig. 4 where the vertical axis is the inverse of the squared capacitance normalized to a unit area.

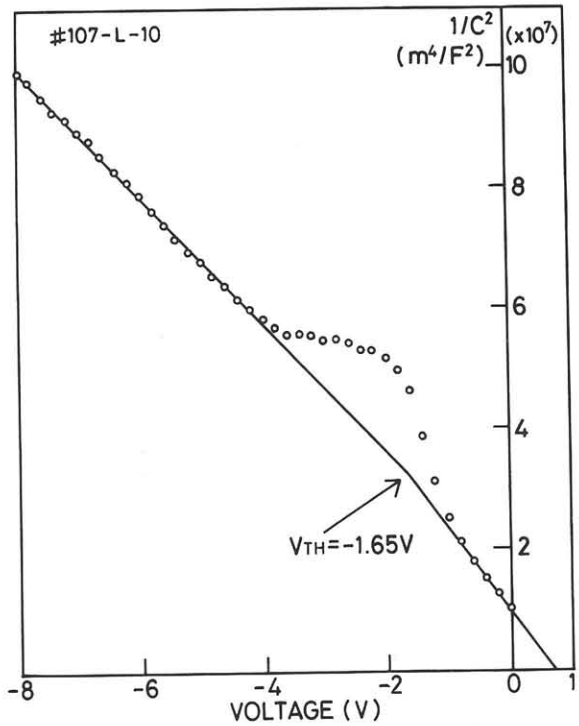


Fig. 4 Capacitance-voltage characteristic of Ag/p-InP/p-InGaAs Schottky diode at RT.

From the C-V characteristic shown in Fig. 4, a carrier concentration profile of the diode was obtained and shown in Fig. 5. Similar spike and notch in the carrier concentration profile at the n-InGaAs/n-InP interface has been reported[4,5]. The feature could probably result from the notch and spike in the valence band which modulate the free carrier concentration near the interface. Since the notch and spike in the valence band are formed at the p-InP/p-InGaAs hetero-interface, the conduction band should have a step at the interface. The step barrier in the conduction band should be surmounted by the electrons in the InGaAs layer to contribute as a current in the diode.

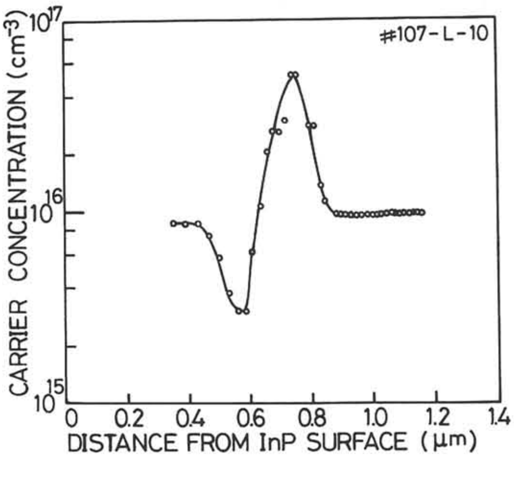


Fig. 5 Carrier concentration profile in the #107 diode which was obtained from the C-V curve in Fig. 4.

## §4. Spectral Response of Ag/p-InP/p-InGaAs Schottky Photodiodes

The spectral response of the Schottky photodiodes have been measured with the applied voltage as a parameter. As mentioned in §3, the electrons generated in the InGaAs layer have to surmount the conduction band step at the p-InP/p-InGaAs hetero-interface. To assist the electrons to flow over the conduction band step, the reverse bias voltage is applied to the Schottky contact so that the step is lowered by the electric field of the depletion layer. Thus, a drastic increase of the photo-excited current should be expected for the longer wavelength region of InGaAs.

The photodiodes were irradiated through the Ag contacts. The light sources were a tungsten-iodine lamp for the visible and infrared region, and a xenon lamp for the violet region. The responsivity of the diodes was calculated from the relative responsivity to the calibrated Ge and Si photodiodes.

The results are shown in Fig. 6. A very wide range of the spectral response of the Ag/p-InP/p-InGaAs Schottky photodiode is demonstrated.

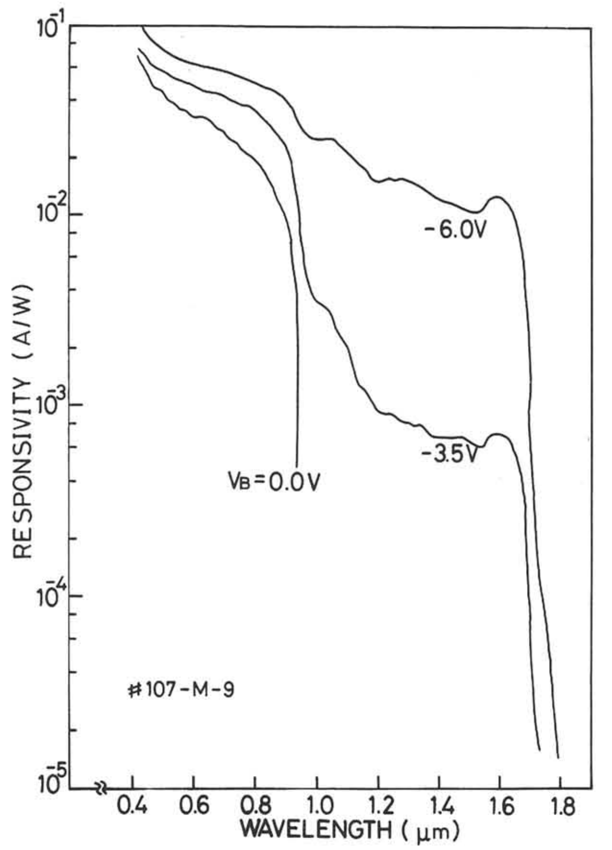


Fig. 6 Wavelength dependence of responsivity of the Ag/p-InP/p-InGaAs Schottky photodiode. Longer wavelength photoresponse which corresponds to that of InGaAs increases drastically with increasing applied voltage.

At the bias voltage zero, the diode has a sharp cut-off of the responsivity at the wavelength 0.92 μm which corresponds to the energy gap of InP( 1.35 eV at RT ). With increasing voltage the responsivity in the longer wavelength region with the cut-off wavelength at 1.65 μm which corresponds to the energy gap of $In_{0.53}Ga_{0.47}As$ ( 0.75 eV at RT ) increases drastically. For example the responsivity in the longer wavelength region at -5 V is by three orders of magnitude higher than that at -1 V. Though the measurement is stopped at the wavelength 0.4 μm, this was limited only by the measurement system. Thus, this Schottky photodiode covers a very wide spectral range from ∿ 0.4 μm to 1.65 μm with a fairly flat wavelength dependence of the responsivity.

The absolute value of the responsivity is not high enough compared with that of InGaAs p-n junction photodiode( $\sim$0.7 A/W )[6]. This is due to a relatively thick film of Ag( $\sim$500 Å ) for the Schottky contact through which the incident light reaches the depletion layer. Thinner Ag film ( 100$\sim$200 Å ) will make the responsivity close to 0.2$\sim$0.5 A/W, since the reflectivity greatly decreases at that film thickness[7].

## §5. Summary

Utilizing the selective etching of InGaAsP and InP, Ag/p-InP/p-InGaAs Schottky photodiodes were fabricated from the multiple layer hetero-structure grown by LPE. With a high enough Schottky barrier at the Ag/p-InP contact( 0.8 eV at RT ) the reverse leakage current was low. By the capacitance-voltage measurement the spike and notch structure in the valence band at the p-InP/p-InGaAs hetero-interface was revealed which is similar to that in the conduction band at the n-InGaAs/n-InP interface. With the applied reverse bias the photoresponse in the longer wavelength region( from 0.92 μm to 1.65 μm ) for InGaAs increased drastically, and a very wide ( between $\sim$0.4 μm and 1.65 μm ) and a fairly flat responsivity has been observed in the Ag/p-InP/p-InGaAs Schottky photodiodes.

The structure here can be activated by Cs coating to form the NEA( negative electron affinity ) of which photomultiplier usually has an extremely high detectivity( $\sim$5000 A/W )[8]. Realization of such a high sensitivity photodetectors in the 1 μm wavelength range, where we have no sufficient detectors, will enable great progress in the investigation of near infrared physics and electronics, *e.g.*, the optical properties of InGaAsP alloy semiconductors and optical fibers.

Acknowledgment

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