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Photoelectrical properties of InP-InGaAsP heterojunction avalanche photodiodes

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Photoelectrical properties and the spectrum of the avalanche multiplication factor versus the reverse voltage at room temperature have been studied for LPE grown for InP-$In_xGa_{1-x}As_yP_{1-y}$ heterostructures. The tunneling current becomes substantial at peak junction electric fields as low as 10^5 V/m due to the small direct energy gaps and small effective masses of the structures tested. The process of breakdown in the investigated structures was of the avalanche type. The results found for the lowering of the tunneling current in the pre-breakdown region. The temperature coefficient of the breakdown voltage $\beta = (1/V_B)\cdot(dV_B/dT) > 0$ was determined in the temperature range 77-300 K and its value was found to be $\beta = 5.78\times10^{-4}$ K^{-1}.

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1. Introduction

The quaternary alloy InGaAsP lattice matched to InP, is a very important material for fabricating optoelectronic devices. Light sources and optical detectors operated in 1.3-1.55 μm range, which is ideally suited for low-attenuation optical-fiber transmission, were developed based on this material [1-4]. Important materials in biological samples have characteristic absorption and reflection in the near infrared region of the spectrum. Therefore, quality control in food industry and clinical diagnostics demand powerful, versatile and relatively not expensive spectrometers. For these applications, the InGaAsP material needs to be of high quality.

Liquid phase epitaxy (LPE) is a well-developed and simple technique that has been proven to have potential in growing high quality InGaAsP layers. Photodiodes made from these materials have been beset by anomalously large dark currents which increase nearly exponen-tially with applied voltage [5-7]. The excess dark current has been attributed to several different sources-for example, surface conduc-tion [8], microplasmas and tunneling [9]. Therefore, an important task is to determine the nature of the excess dark current in structures based on InGaAsP and ways of reducing this current by improving the technology of fabrication of these structures.

The present paper reports on $In_xGa_{1-x}As_yP_{1-y}$ / InP (y=0.68) double hetero-structures with reverse current characteristics which can be remarkable well fit to a wide range of applied voltages and temperatures using a theory that takes account only of current originating from band to band tunneling component. The dark current–voltage characteristics were investigated and analyzed in the temperature range of 77-373 K.

2. Experimental methods

InGaAsP / InP double heterostructures were grown in a computer controlled LPE apparatus equipped with a multibin slider boat. Single phase melts with relatively high super-saturations were applied for all growth experiments. Four-layer structures were grown on (100)-oriented InP ($p=2x10^{18}cm^{-3}$) substrate consisting of an p-InP buffer layer (3-5 μm), an p-InGaAsP active layer (2-3 μm), and heavily n-type InP top layer. The p-type and n-type layers were doped with Zn and Sn, respectively.

Mesa-diode samples with a sensitive area 250-850 μm in diameter were fabricated from these structures by standard photolithography. The mesas were mounted on TO-18 headers in a conventional way. A cross-sectional sketch is shown in Fig. 1.

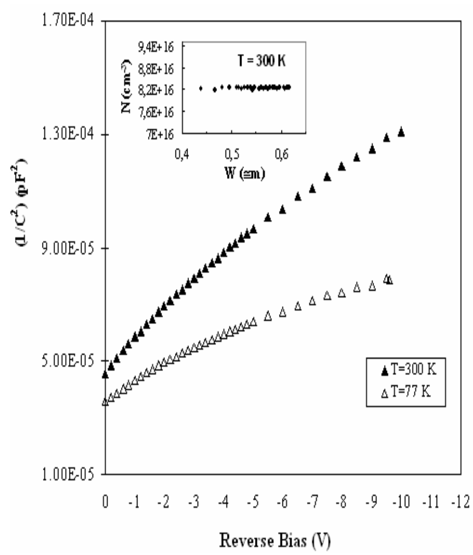

Fig.1. Typical C-V characteristic of the InP- InGaAsP avalanche photodiodes at several temperatures. In the inset: calculated doping profile obtained from C-V measured data.

The breakdown voltages of all structures were within the range 10-11.5 V. An abrupt junction was found by *C-V* measurements, with electron concentration 8.2×10^{16} cm^{-3} in the p-InGaAsP layer. Fabricated devices were mounted into a glass Dewar with a cold shield for detailed electrical measurements at variable temperatures. *I-V* characteristics of the samples were measured using a KEITHLEY 6487 pA meter and *C-V* characteristics by KEITHLEY 590/1M *C-V* Analyzer. The photosensitivity spectra were measured with SPM-2 monochromator equipped with a LiF prism and with the use of a tungsten lamp light source. All measurements were controlled by a computer via an IEEE-488 standard interface so that the data collecting, processing and plotting could be accomplished automatically.

3. Results and discussion

The capacitance-voltage (*C-V*) characteris-tics are one of the fundamental properties of the p-n junction diode structures. Fig. 1 shows the capacitance-voltage characteristics taken at a temperatures T = 77 K and 300 K with frequency f =1 MHz. The characteristics are satisfactorily described by the dependence $C^{-2}\sim V$, typical of a abrupt junction. The gradient of the $C^{-2}=f(V)$ curve leads to a carrier concentration of N_A = 8.2 x10^{16} cm^{-3} in the p-InGaAsP layer.

We determined the dependence of the reverse current in a structures (under a fixed bias voltage) on the mesa diameter. When the MESA diameter was in excess of 400 µm, the dependence became nearly quadratic, typical of the bulk current. A similar investigation made it possible to select for our measurements those structures in which the reverse current included only a small contribution of the surface component.

The observed dependence of current on temperature and applied voltage is shown to be consistent with the tunneling model. Band-to-band tunneling current in reverse-biased, direct gap semiconductors is given by:

$$I_{tun} \cong \gamma A \exp\left[\frac{-\theta\sqrt{m_0}(E^*)^{3/2}}{q\hbar E_m}\right] \quad (1)$$

Here, m^* is the effective mass of the tunneling carrier, m_0 is the free electron mass, $\hbar$ is Planck's constant divided by 2π, and E^* is the tunneling energy or the height of the tunnel barrier which in the band-to-band case should be equal to the band gap E_g, E_m the maximum electric field, A the junction area, q the electronic charge. The parameter θ is given by $\theta=\alpha\sqrt{(m^*/m_0)}$, where α is a constant, which depend on the detailed shape of the tunneling barrier, is on the order of unity for band-to-band processes. This value lies between α =1.11 for band-to-band tunneling through a triangular barrier, and α =1.88 for band-to-band tunneling through a parabolic barrier [10]. Eq. (1) is valid when $|V+V_{bi}|\geq\frac{E_g}{q}$, where V_{bi} is the built-in potential of the junction. Finally, the prefactor γ depends on the initial and final states of the tunneling carrier; for band-to-band tunneling,

$$\gamma=\left(\frac{2m^*}{E_g}\right)^{1/2}\frac{q^3E_mV}{4\pi^2\hbar^2} \quad (2)$$

where V the applied voltage across the junction.

The experimental current-voltage charac-teristics in the reverse bias region for several temperatures are shown in Fig. 2.

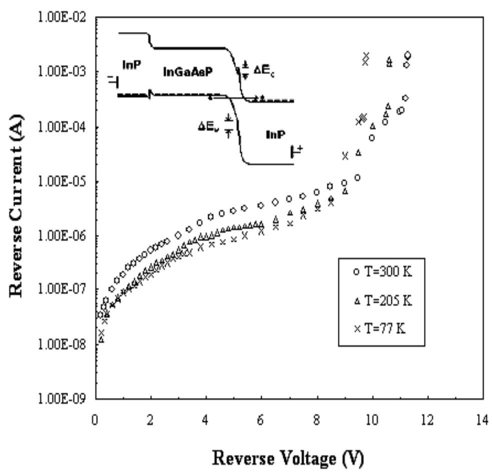

Fig. 2. I-V characteristics of a reverse-biased InP-InGaAsP avalanche photodiodes at several temperatures. The energy band diagram of a InP-InGaAsP heterostructure under reverse bias is shown in the inset.

It is seen that at the whole of temperature range and at a wide range of reverse bias voltages, the reverse current varies exponentially with applied voltage, indicating that the tunneling current mechanism prevails. The current is found to increase nearly exponentially with applied voltage-a behavior uncharacteristic of either generation–recombination or diffusion leakage currents. The tunnel component of the current predominates up to nearly the break-down value. Nevertheless, in the investigated structures the breakdown was of purely avalanche nature, as indicated by the temperature coefficient of the breakdown voltage

$\beta=(1/V_B)\cdot(dV_B/dT)>0$, which was positive in the investigated temperature range 77-373 K. The values of this coefficient were $\beta=5.78\times10^{-4}$ K^{-1}, in good agreement with the values of the same coefficient reported for other III–V semiconductors. Fig. 3 shows the temperature dependence of the reverse break-down voltage V_B. It can be seen that the V_B has a positive temperature coefficient with κ_B = +6.76 mV K^{-1} and increases to 11.75 V at 373 K. Clearly, this is due to the avalanche breakdown mechanism. For an abrupt junction, the avalanche breakdown voltage at room temperature is approximately given by a uni-versal expression [10],

$$V_B = 60\left(\frac{E_g}{1.1}\right)^{3/2}\left(\frac{N_B}{10^{16}}\right)^{-3/4} \qquad (3)$$

where N_B is the impurity concentration in the lightly doped side of the p-n junction. Assuming that Eq. (3) is also valid for heterostructures, then for $N_B = N_A = 8.2\times10^{16}$ cm^{-3} (*C-V* measurement result), we obtain V_B (300 K) = 11.4 V, which is in good agree-ment with the experimental value of about 11.28 V.

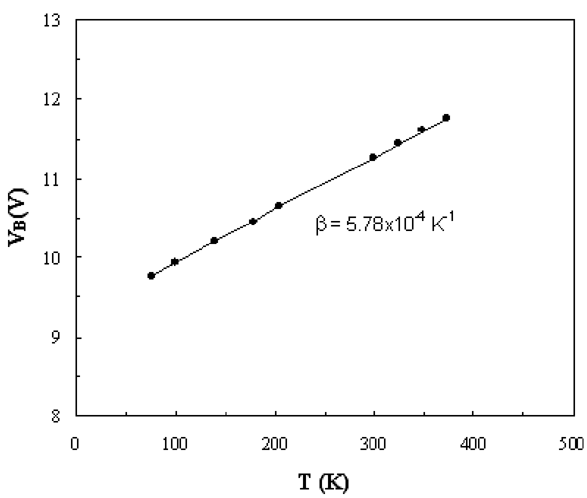

Fig. 3. The temperature dependence of the breakdown voltage.

The spectral dependence of the absolute quantum efficiency for investigated photodiodes was measured using a tungsten lamp monochromator source and standard phase-sensitive electronics, under computer control. The absolute quantum efficiency was established using a GaAs laser source and previous-ly calibrated detector. The results of this measurements are presented in Fig. 4. The short wavelength limit near 0.9 µm occurs because of the absorption edge in the InP windows. At longer wavelengths, the efficiency rises abruptly to a maximum of 60-70% near 1.0 µm and then decreases gradually to the long-wavelength cutoff λ_C near the quaternary band gap. With the application of an appropriate antireflection coating, the maximum efficiencies should approach unity.

As stated above, photocurrent in this structures is measured by using GaAs laser to generate carriers. The beam from the laser is split and chopped at two different frequencies, with the light at one frequency focused on the top of the MESA and the light at the other frequency simultaneously focused on the bottom of the well (Note that the light was coupled to the sample via an optical fiber). The resulting photocurrents are detected by lock-in amplifiers referenced to the two different chopper frequencies. The photocurrent is measured as the reverse-bias voltage is increased up to the breakdown voltage. The data are taken under computer control and stored for subsequent analysis.

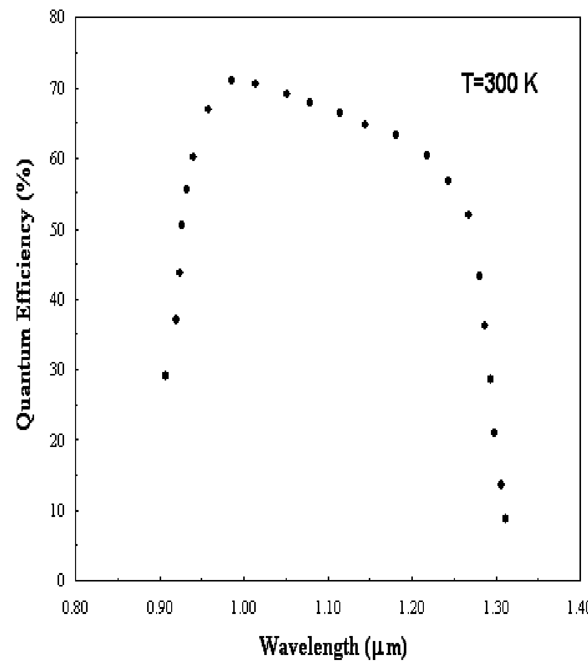

Fig. 4. External quantum efficiency versus wavelength for InP-InGaAsP avalanche photo-diodes.

The current multiplication is calculated from the measured photocurrent and the calculated injected primary photocurrent. The primary photocurrent is modeled as a sheet of current generated at the illuminated surface with the minority carriers diffusing to the edge of the depletion region where they are collected. Division of the measured photocurrent by the current calculated for the corresponding bias voltage from the above model gives the current multiplication. The ionization coefficients are calculated from the multiplication by using the standard analytical expressions. The resulting ionization coefficients are shown in Fig. 5. The breakdown voltages for the investigated structures measured can be calculated by using the ionization coefficient data shown in Fig. 5. The calculated breakdown voltages can be compared to the actual experimentally measured breakdown voltages to check on the self-consistency of the data. The experimental and calculated breakdown voltages typically agree to within 1.87%.

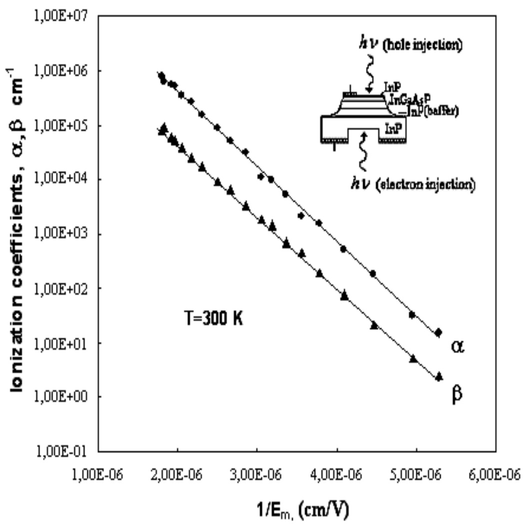

Fig. 5. Impact ionization coefficients versus electric field for InP-InGaAsP avalanche photo-diodes at room temperature.

4. Conclusions

We have presented evidence that a significant source of reverse-biased junction dark current in InP-InGaAsP structure is due to tunneling, and further that the data are in good agreement with prediction for a band-to-band process. However, our measurements do not preclude the possibility of tunneling via traps in the band gap. Indeed, trap-assisted tunneling has many of the same characteristics as the more fundamental band-to-band process.

The presence of tunneling sets limits on the magnitude of the electric field allowable in the junction region above which the dark current becomes prohibitively large. In our devices, we find that tunneling is the dominant source of leakage over a wide range of applied voltages when the doping density is greater than 8×10^{16} cm^{-3}. The limitation set on electric field has significant impact on the capabilities and design considerations in several device applications. Our results, which are consistent with a previous study on several III-V compounds including InGaAsP, indicate that it may be difficult to make sensitive avalanche photo-detectors from these materials with doping levels as high as 8×10^{16} cm^{-3} owing to the presence of large tunneling currents which are a significant source of detector noise.

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