JOURNAL OF OPTOELECTRONİCS AND ADVANCED MATERİALS Vol. 9, No. 11, November 2007, p. 3567 - 3570

Dark currents ın the uncooled InAs / InAsSbP photodıodes for the spectral range 1.6 - 3.5 μm

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The electrical characteristics of photodiode structures on the base of InAS/InAsSbP heterojunctions, that have a high room-temperature differential resistance and operate in the mid-infrared region over the wavelength range 1.6-3.5 μm are reported. As a result of C-Vmeasurements, the obtained p-n heterojunctions were abrupt, with $1/C^2 \sim V$, and the impurity concentration in the weakly doped region was (5-7)×10^{15} cm^{-3} at room temperature. An experimental investigation of current-voltage characteristics has been done in the temperature range 77-340 K, and have been determined the mechanism of the flow of dark currents in InAS/InAsSbP heterojunction photodiodes.

(Received August 10, 2007; accepted November 1, 2007)

Keyword: Dark currents, photodiode structures, liquid phase epitaxy (LPE)

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1. Introduction

Infrared photodetectors operating in the range 1.8-3.4 μm have wide ranging applications and in particular are important components of methane gas and water vapour detectors. At the moment the dominant infrared material systems for these applications in this wavelength region are PbSe and HgCdTe. However, both these materials not only suffer from undesirable noise problems but also require thermoelectric cooling below room temperature in order to get a sufficiently high detectivity required for successful instru-mentation. This significantly restricts their use in portable gas detection systems, infrared spectrometers, thermal imaging cameras and other applications. The need to provide cooling of the detector element makes the overall system cumbersome and unsatisfactory because of the power requirements for thermoelectric cooling. In addition both PbSe and HgCdTe are normally used in the photoconductive mode and have a relatively slow response speed which limits the modulation frequency and the integration time of the final gas sensor instrument.

Much attention has been given to InAs and InAs based alloys (InAsSbP, InGaAs and InAsSb) [1] as an attractive material for the fabrication of optoelectronic devices in the near to middle infrared wavelength region [2-6].

Photodetectors based on InAs and its solid solutions, which possess a high sensitivity when cooled (T = 78-195 K), have been known for the region 2-2.5 μm for many years now [7-9]. The small band gap and high conductivity of these materials, however, cause certain difficulties in designing photodetectors to operate without cooling in the spectral region above 2.5 μm (low resistance, high dark currents, etc.). A measure that promises to reduce the dark current in long-wavelength photodiodes is to use heterostructures, in which the nonphotoactive regions are made of wide-gap materials.

We presented results of investigations the electrical properties of InAs / InAsSbP heterojunction photodiodes with high room-temperature differential resistance.

2. Device fabrication and measurements

The structures studied were fabricated by the liquid-phase epitaxy (LPE) method. A wide-gap layer of InAsSbP solid solution ($E_g = 0.5$ eV, $T = 300$ K), doped with Zn acceptor impurity, was grown on a substrate of undoped InAs ($n = 2\text{x}10^{16}$ cm^{-3}). As in known, the wide-gap “window” layer lowers the surface recombination velocity and makes it possible to avoid problems associated with the inversion layer on the surface of p-type InAs [10]. As shown results of X– ray analyzing that, due to a high segregations factor of zinc (Zn), the p-n junction has been displaced from heteroboundary in to InAs region on depth of 5-30 μm. Since the thickness of InAsSbP is 2-3 μm, the p-n junction is laid in InAs region.

Photosensitive structures were fabricated by the photolithographic method as mesa diodes with a sensitive-area diameter of 300-450 μm. In developing and optimizing the design of uncooled heterophotodiodes, the geometrical parameters of the p-n junction is important. This information can be found out with a scanning electron microscope when current is induced by an electron probe. Such studies had not been carried out before since such conditions are difficult to realize at room temperature for narrow-gap materials of the InAs type. The good quality of the structures obtained enabled us to use the induced-current method [5]. The current-voltage (I-V) measure-ments were performed by the use of Keithley 6487 picoammetre/voltage source and capacitance-voltage measurements were per-formed by the use of KEITHLEY 590/1M *C-V* Analyzer using a temperature-controlled Janis CCS-150 cryostat, which enables us to make measurements in the temperature range of 77K-340K. All measurements were controlled by a computer via an IEEE–488 standard interface so that the data collecting, processing and plotting could be accomplished auto-matically.

3. Experimental results and discussion

Fig. 1 shows the capacitance-voltage characteristics of InAS/InAsSbP heterojunction photodiodes, taken at a temperature T=300 K and frequency f =1 MHz. The characteristics are satisfactorily described by the dependence $C^{-2} \sim V$, typical of an abrupt junction. The $C-V$ dependence can be interpreted by the law,

$$\frac{1}{C^2} = \frac{2(V_R + V_B)}{q\varepsilon_S N_D A^2} \tag{1}$$

Where A, is the area of the diode, V_R the reverse bias voltage, V_B is the built in (diffusion) potential at zero bias and is determined from the extrapolation of the $1/C^2 - V$ plot to the V-axis, ε_S is the dielectric constant of the InAs, q is the electronic charge and N_D is the doping concentration.

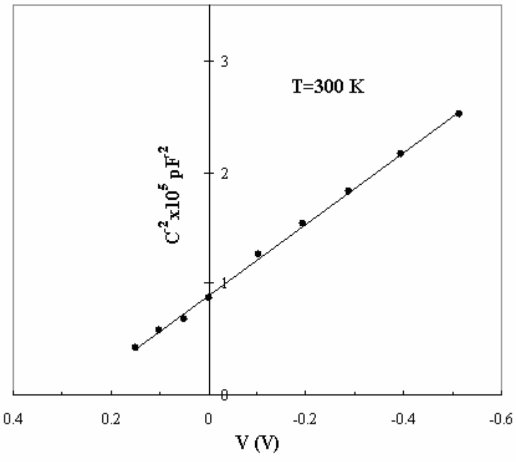

Fig. 1. The room temperature 1/C^2-V charac-teristics of InAs / InAsSbP photodiode.

The slope of the $C^{-2} = f(V)$ curve leads to a carrier concentration in the p-InAS region $N_d = (5\text{-}7)\times10^{15}$ cm^{-3}. The intercept voltage V_B in the C^{-2} vs V plots was found to be 0.31 ± 0.02 V.

The current-voltage characteristics were investigated at temperatures over the range from 77 to 340 K. According to the results of analysis the forward branches of the current-voltage characteristics, the dependence of forward current on voltage may be described by this empirical expression:

$$I = I_0 \exp\left({eV}/{\beta kT} \right) \tag{2}$$

where β is the ideality factor. The measurements is shown in Fig. 2, which the ideality factor β is increased with decreasing temperature, from β=1.06 at temperatures over the range T = 340 – 230 K to β=2.9 at the T= 77 K (see Fig.3).

At temperatures over the range from 340 K to 230 K and 230 K to 160 K the forward current was determined by a to different mechanisms of the flow of the current, by diffusion and recombination mechanisms, respectively. At the low temperatures (T ≤ 150 K) the contribution of tunneling component was carry in essential to the mechanism of the flow of the current.

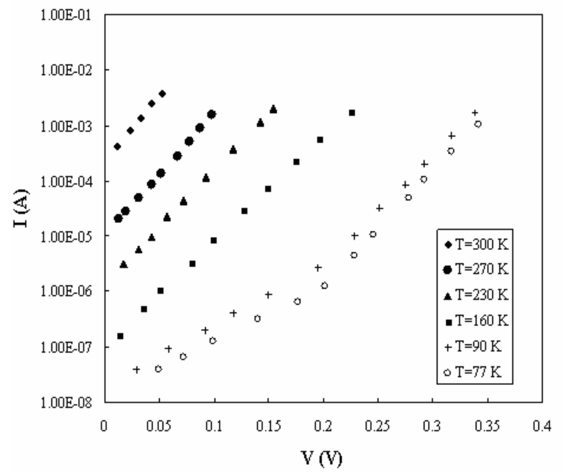

Fig. 2. Forward bias I_F - V_F characteristics of InAs / InAsSbP photodiode in semi-logarith-mic scale at several temperatures.

This was proved by the weak dependence of the forward current on temperature at this temperature region.

Fig. 3 shows the reverse current – voltage characteristics at several temperatures. It is seen that, whereas in the temperature range from 270 K ≤ T ≤ 340 K and in the range of voltage from 0.1 to 1V, the reverse current was defined by the diffusion mechanism and obeyed an expression:

$$I = I_0 \left[\exp\left({eV}/{\beta kT} \right) - 1 \right] \tag{3}$$

where I_0 = 300 μA at room temperature.

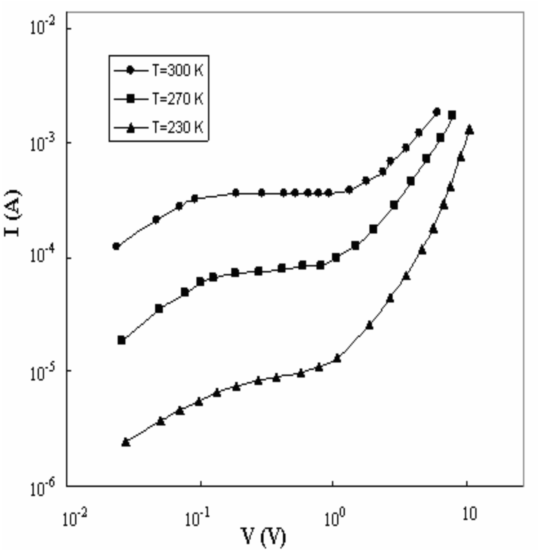

Fig. 3. Reverse bias I_R - V_R characteristics in logarithmic scale at several temperatures.

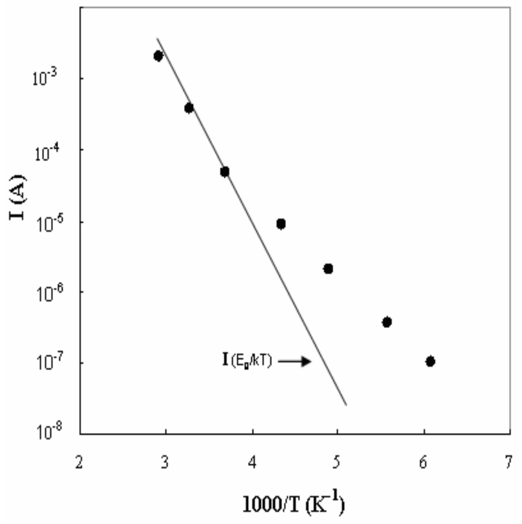

Fig. 4. The reverse current as a function of reciprocal temperature at V = -0.5 V reverse applied bias. Full line show the calculated dependence for diffusion current.

At temperatures over the range from 250 K to 160 K, a quadratic dependence of the current on the bias is observed for small biases, thus indicating the predominance of the generative character of the current. The generation and subsequent separation of carriers occur in the space-charge region of the *p-n* junction in the narrow-gap p-InAs layer. The effective carrier lifetime τ_{eff} was determined from this portion of the *I-V* characteristic, using the known relation for the generation-recombination current [11]

$$I = \frac{en_i WA}{\tau_{eff}} \tag{4}$$

where A is the *p-n* junction area, *W* is the width of the space-charge region (proportional to $\sqrt{V}$), e is the electron charge, and n_i is the intrinsic carrier concentration at a given temperature. The values obtained are $\tau_{eff} \approx 6.7\text{x}10^{-6}$ s agrees well the radiative recombination time in p - InAs [12]. The effective carrier lifetime is a key factor in the detectivity of a photodetector operating at about room temperature in the photovoltaic mode. Therefore, further improvement of the photodiodes under study requires that the carrier lifetime should be made longer.

Fig. 4 shows the temperature dependence of the reverse current at a bias V=0.5 V. The activation energy, determining by this dependence whereas in the temperature range from 250 K $\leq T \leq$ 340 K was E_a = 0.34 eV, this value was very nearly to band gaps value of narrow-gap structure. This is evidence of the diffusion mechanism of the flow of dark current. Whereas in the temperature range from 160 K $\leq T \leq$ 250 K the activation energy was E_a = 0.2 eV, this value was very nearly to a half band gaps value of narrow-gap structure. This is evidence of the generation mechanism of the flow of dark current [11]. In Fig. 4 also shows the calculated temperature dependence for the diffusion mechanism of the dark current. Obviously, at high temperatures the experimental data agree better with the dependence for the diffusion current. This kind of current has a temperature dependence of the form $I \sim T^{3/2} \exp(-E_g/kT)$. The deviation of the experimental dependence from calculated dependence for the diffusion current is due to growth of the effect of the generation-recombination component of the dark current with activation energy E_a = 0.2 eV $= E_g/2$ (E_g = 0.42 eV in InAs at 77 K) . The reverse current at V >5 V increased exponentially with the voltage and according to our estimates, was determined by inter-band tunneling This is also confirmed by the weak temperature dependence of the current under reverse biases V >5 V.

The R_0A product is plotted against $1/T$ for a typical 400 μm diameter photodiode in figure 5. Using a semilog scale representation R_0A varies linearly for the diffusion and generation-recombination mechanisms, as $1/n_i^2$ and $1/n_i$, respectively [13]. In the temperature range above 250 K, the R_0A product follows the diffusion model with a slope of 3.6, whereas in the temperature range 160 K $\leq T \leq$ 250 K, R_0A fits a generation-recombination model with slope of 2.3. Therefore, we assume that the operation of our single heterojunction InAS / InAsSbP photo-diode is bulk-limited near room temperature.

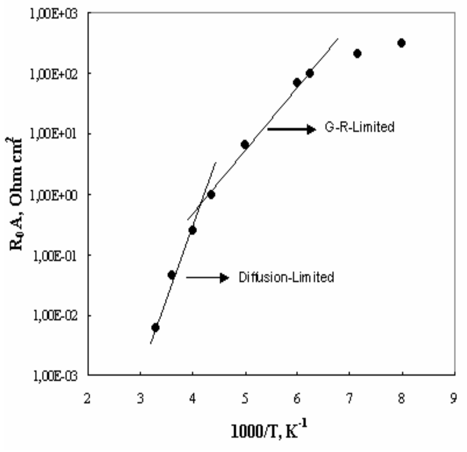

Fig. 5. Temperature dependence of the R_0A product of typical 400 μm diameter InAs/InAsSbP photodiode. Full lines show the theoretical fit for diffusion-limited and generation - recombination (G - R) limited mechanisms.

4. Conclusion

In conclusion, we must point out one more prospect for the application of the structures studied, the possibility of their being used as a basis for fabricating avalanche photodiodes. It would operate under slight cooling, which is important for their use in infrared fiber-optics communication systems based on fluoride and chalcogenide glasses. Previous studies showed that in materials of the type InAs, GaSb and their solid solutions, in which there is band "resonance" $E_g = \Delta_0$ (Δ_0 is the magnetitude of the spin-orbit splitting of the valence band), one can obtained a high ratio of the electron and hole impact ionization coefficients, β/α >>1, and low excess noise of avalanche photodiodes. In our study we observed avalanche multiplication of the photocurrent in InAs/InAsSbP photodiodes even at room temperature with multiplication factors $M \geq$ 5. This multiplication is probably also reeponsible for the growth of the dark current at V > 1V. The results of our study of avalanche multiplication in such photodiodes at near room temperatures will be published. Meanwhile, the low dark current and high R_0A product obtained over a significant region of the mid-IR region demonstrates the high quality of the devices and the epitaxial layers which can be easily achieved with bulk LPE material having low point defect density. Furthermore, unlike the PbS and PbSe photoconductors, the InAs/InAsSbP photo-detector operates in the photovoltaic mode and has an improved noise performance with high stability, fast response and does not require a bias current for operation. These features, together with high efficiency at room temperature makes the InAs/InAsSbP photodiodes potentially a very attractive choice for a wide variety of mid-infrared detector applications.

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