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Avalanche multiplication in photodiode structures using GaInAsSb solid solutions

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The first successes in the development of optical fibers for the IR part of the spectrum[1,2] (2-4 μm), where low losses, 10^{-2}-10^{-3} dB/km, are expected, stimulated the development of light sources[3,4] and photodetectors[5] for this spectral region. In Ref. 5 we reported the development of fast photodiodes using multicomponent GaInAsSb/GaAlAsSb solid solutions. Of primary interest for applications in optical-fiber data transmission systems, however, where the detector must be highly sensitive over a wide frequency band, are photodetectors with an internal gain, especially avalanche photodiodes.

In this paper we report a study of avalanche multiplication of the photocurrent in GaInAsSb structures.

The structures were fabricated by liquid-phase epitaxy on n-type GaSb (111) substrates, doped with Te to a carrier concentration of $(5\text{-}7)\cdot 10^{17}$ cm^{-3}. The structures were actually double heterostructures, in which a narrow-gap n-$Ga_{0.80}In_{0.20}As_{0.17}Sb_{0.83}$ active layer (E_g = 0.52 eV at 296 K) is sandwiched between a wide-gap n-$Ga_{0.66}Al_{0.34}As_{0.025}Sb_{0.975}$ buffer layer with a carrier concentration $(1\text{-}3)\cdot 10^{17}$ cm^{-3} and a wide-gap p-GaAlAsSb layer (the "window") of the same composition (E_g = 1.1 eV), doped with Ge to a hole concentration of $(1\text{-}3)\cdot 10^{19}$ cm^{-3}.

Mesa photodiodes with a working area 300-400 μm in diameter were fabricated from these structures by photolithography (Fig. 1a).

We studied the voltage–capacitance characteristics, the inverse branches of the voltage–current characteristics, the photosensitivity spectrum, and the avalanche multiplication of the photocurrent as functions of the wavelength of the light and the temperature over the range 78-296 K. The spectra were measured with an SPM-2 monochromator equipped with a LiF prism, and with the use of a globar light source.

According to the C–V measurements, the p–n junctions obtained were sharp, with $1/c^2 \sim V$, and they had a wide space-charge region, which lay for the most part in the narrow-gap active region $W_0 = 3.0\cdot 10^{-5}$ cm. The carrier concentration in the narrow-gap region was estimated to be $(5\text{-}7)\cdot 10^{15}$ cm^{-3}. The maximum electric field at a zero voltage was $E_m = 2.3\cdot 10^4$ V/cm. The current density at reverse voltage V = 1 V was $j = (2.8\text{-}3.5)\cdot 10^{-3}$ A/cm^2. The reverse current at V > 5 V increased exponentially with the voltage and, according to our estimates, was determined by interband tunneling. The breakdown voltage of these structures, defined by an inverse current of 10^{-3} A, lay in the interval 20-25 V at T = 296 K and in the interval 30-35 V at T = 78 K.

Figure 1 shows the photosensitivity spectrum of GaInAsSb/GaAlAsSb structures at three temperatures: 296, 196, and 78 K. From the shift of the long-wavelength edge of the photoresponse, we estimated the temperature coefficient of the gap width of the GaInAsSb solid solution. The average result turned out to be $\Delta E_g/\Delta T = 4.1\cdot 10^{-4}$ eV/K. In the interval 1.5-2.2 μm the quantum efficiency without gain is 0.4-0.6 A/W at 296 K.

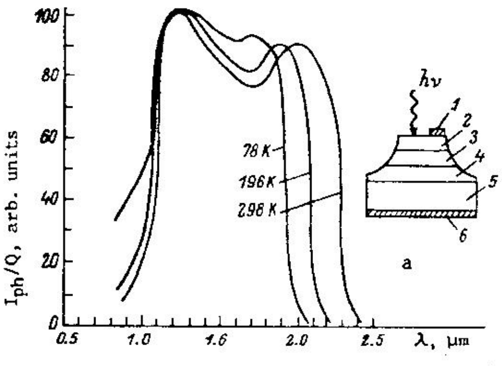

FIG. 1. Photosensitivity spectrum of GaInAsSb/GaAlAsSb diode structures at 296, 196, and 78 K. Inset a is a diagram of the photodiode structure. 1, 6) Ohmic contacts; 2) wide-gap p^+-GaAlAsSb "window"; 3) narrow-gap n-GaInAsSb active region; 4) n-GaAlAsSb wide-gap buffer layer (E_g = 1.1 eV); 5) n-GaSb (111) substrate.

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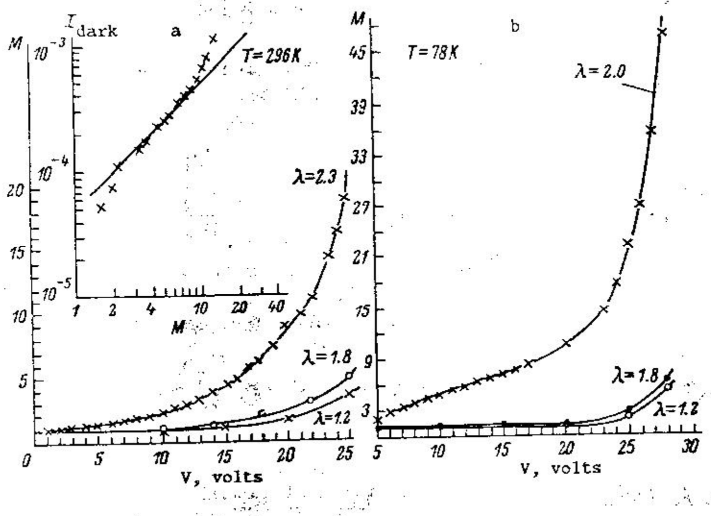

FIG. 2. The charge-carrier multiplication factor in GaInAsSb/GaAlAsSb structures versus the reverse voltage for illumination with monochromatic light at one of several wavelengths. a) T = 296 K; b) T = 78 K. The inset in Fig. 2a shows the dark current through the structure versus the photocurrent multiplication factor at T = 296 K.

Figure 2a and b, shows the spectrum of the avalanche multiplication factor versus the reverse voltage at temperatures of 296 and 78 K. These curves were recorded by illuminating photodiode structures through the wide-gap p-GaAlAsSb layer with monochromatic light of various wavelengths. We see from these figures that the multiplication factor increases with increasing wavelength of the light absorbed in the narrow-gap layer.

The multiplication factor, defined as the ratio of the photocurrent multiplied at the given voltage to the initiating photocurrent, $M = I_{ph}(V)/I_{ind}(Q)$, depends very strongly on the level of the initial value of the initiation photocurrent, decreasing as this current increases (Fig. 2b). The maximum values of the multiplication factors were M = 10-20 (T = 296 K) and M = 50-100 (T = 78 K). In some of the diodes we achieved a multiplication factor $M = 4\cdot10^2-2\cdot10^3$ (78 K) at an initiating photocurrent $I_{ind} = 5\cdot10^{-9}$ A and at a wavelength λ = 2 μm.

It can be seen from Fig. 2 that the multiplication factor increases with increasing wavelength of the light. Since the space-charge region lies essentially entirely in the narrow-gap n-type region, with a maximum electric field near the interface with the wide-gap p-GaAlAsSb layer, which is illuminated, this result is evidence of a predominant multiplication of holes in the n-type region. The ratio of ionization coefficients was estimated from data on the multiplication: $\beta/\alpha = M_{p-1}/M_{n-1}$, where the hole and electron multiplication factors, M_p and M_n respectively, were chosen be equal to their values at λ = 2 μm and λ = 1.2 μm, respectively, for the same electric field ($E \approx 2\cdot10^5$ V/cm). It turns out that the ratio β/α increases with decreasing temperature, changing from $\beta/\alpha \geq 5$ at 296 K to $\beta/\alpha \geq 10$ at 78 K. We regard these as preliminary estimates.

Previous studies of avalanche multiplication and of the hole and electron ionization coefficients in the binary compounds InAs and GaSb and also in several solid solutions of these compounds (Refs. 6 and 7 for example) have shown that the hole ionization coefficient is significantly greater than the electron ionization coefficient because of the particular band structures of these materials (primarily, the band "resonance" $E_g \approx \Delta_0$). Specifically, the impact ionization is dominated by holes that are from the spin–orbit split valence band and for which the threshold for impact ionization is at a minimum and is close to $\varepsilon_{ih} \approx E_g \approx \Delta_0$. In structures made from GaInAsSb solid solutions grown on GaSb substrates with a (111) orientation, the electron energy at the threshold for impact ionization ($\varepsilon_{ie} \geq 0.52$ eV at 296 K) exceeds the energy gap between the Γ valley and the low-lying L side valley (according to our estimates, $\Delta_h \approx 0.3$ eV). As a result, hot electrons are scattered into valley, their mean free path for phonon scattering is reduced, and the probability for impact ionization by electrons is reduced. At the same time, the spin–orbit splitting Δ_0 in these solid solutins is not much greater than E_g (in GaSb, Δ_0 = 0.76 eV; in InAs, it is 0.41 eV; according to estimates, in the solid solution GaInAsSb it is $\Delta_0 \leq 0.68$ eV) the contribution of holes from this band will thus still be large (for heavy holes, the threshold for direct impact ionization is far higher: $\varepsilon_{ih} \approx 2E_g \geq 1$ eV).

The plot of the photosignal versus the multiplication factor is linear over the entire range of multiplication factors (up to 10^2-10^3 at 78 K). The dark current in the voltage interval 10-20 V at 296 K and in the interval 20-30 V at 78 K is also multiplied, as the photocurrent is (see the inset in Fig. 2a). This result is evidence that the multiplication in these structures is of a bulk nature and that there are no microscopic plasmas.

Interestingly, in the GaInAsSb/GaAlAsSb heterostructures the potential jump in the valence band at the heterojunction is very low,[9] $\Delta E_V < 0.1$ eV. This result suggests that these structures will not present problems associated with the accumulation of holes at the heterojunction. In InGaAs/InP avalanche photodiodes, for example, that effect degrades the speed

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ossing of an interface by a nonuniform wave without refraction

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Several recent papers have called attention to behavior of electromagnetic waves at surfaces and rfaces between media,[1] because of the practical ortance of the results. It has been shown that, pplied to nonuniform waves of this sort (polari- and magnons), certain obvious concepts come er doubt or lose their original meaning,[2] and new ects appear in the more complicated cases, with an bitrary relative orientation of the waves and the undaries.[3] Let us examine the crossing of an in- rface between two absorbing media by a nonuniform ve which is oriented in an arbitrary way with spect to the interface. The effective refractive dices for the phase normal $\vec{h}$ and the amplitude ormal $\vec{\tau}$ are written[4]

$$N_e=\frac{|\vec{h}'|}{|\vec{h}|}=\frac{1}{|N|}\frac{\sqrt{ch^2\vartheta'-\sin^2\delta_2}}{\sqrt{ch^2\vartheta-\sin^2\delta_1}};\quad K_e=\frac{|\vec{\tau}'|}{|\vec{\tau}|}=\frac{1}{|N|}\frac{\sqrt{ch^2\vartheta'-\cos^2\delta_2}}{\sqrt{ch^2\vartheta-\cos^2\delta_1}}. \quad (1)$$

The phase factor of the wave field is chosen in the form $\exp[-ik(\vec{h}+i\vec{\tau}),\vec{r}]$, where $\vec{h}+i\vec{\tau}=N_1\vec{e}=N_1(\vec{e}_1+i\vec{e}_2)$ is the complex wave normal of the (incident) wave, and $N=n_1-i\varkappa_1=n_1(1-i\,tg\,\delta_1)$ is the complex refractive index of the first medium. The parameters of the waves in the second medium, with refractive index N_2, are primed; $N=N_1/N_2=m-i\chi$; and we specify the vectors $\vec{e}_1$ and $\vec{e}_2$ to be

$$\vec{e}_1=ch\vartheta\{\sin\alpha,\,0,\,\cos\alpha\},\quad \vec{e}_2=sh\vartheta\{\cos\alpha\cos\eta,\,\sin\eta,\,-\sin\alpha\cos\eta\},$$

where α is the angle of incidence, and ϑ and η are the nonuniformity and the noncoplanarity parameters. The nonuniformity parameter of the refracted wave, ϑ', which appears in (1) is found from the laws for refraction[5]:

$$2ch^2\vartheta'=C+\sqrt{C^2-4(A^2+D^2)},$$

$$A^2=(m\,ch\vartheta\sin\alpha+\chi\,sh\vartheta\cos\alpha\cos\eta)^2+(\chi\,sh\vartheta\sin\eta)^2,$$

$$C=1+|N|^2(sh^2\vartheta\sin^2\alpha\sin^2\eta+sh^2\vartheta+\sin^2\alpha),$$

$$D=|N|^2 sh\vartheta\,ch\vartheta\sin\alpha\sin\eta.$$

The representation which we have chosen for the nonuniform waves makes it possible to study certain features of N_e and K_e. It follows from (1) that there exist waves and media such that $N_e=1$; i.e., the wave crosses the interface without being refracted (the angle of incidence is equal to the angle of refraction and is nonzero). For this case the angle of incidence α is found from the equation ($\alpha\neq 90°$)

$$(M+S\,sh^2\vartheta\sin^2\eta)\,tg^2\alpha+m\chi\,sh\,2\vartheta\cos\eta\,tg\,\alpha+L=0 \quad (2)$$

where

$$L=sh^2\vartheta(\chi^2-F|N|^2)-F(1-F),$$

$$M=ch^2\vartheta(m^2-F|N|^2)-F(1-F),$$

$$S=(\chi^2-F|N|^2)+|N|^4ch^2\vartheta,$$

$$F=\sin^2\delta_2+|N|^2(ch^2\vartheta-\sin^2\delta_1).$$

By definition, the angle of incidence is a real number, and so we find the following condition, which restricts the values of the other parameters of the problem:

$$m^2\chi^2 sh^2\vartheta\,ch^2\vartheta-ML\geq\sin^2\eta\,sh^2\vartheta(m^2\chi^2ch^2\vartheta+SL). \quad (3)$$

The crossing of an interface without refraction is not a new effect,[6] although it refers to the case in which a wave is incident from an insulator on a metal, and necessarily involves transformation of the uniform incident wave into a nonuniform refracted wave. This particular case follows from (2) with $\vartheta=0$ and $\kappa=0$:

$$\cos^2\alpha=\frac{n_2^2}{n_1^2}\,\frac{\varkappa_2^2}{n_1^2+\varkappa_2^2-n_2^2}. \quad (4)$$

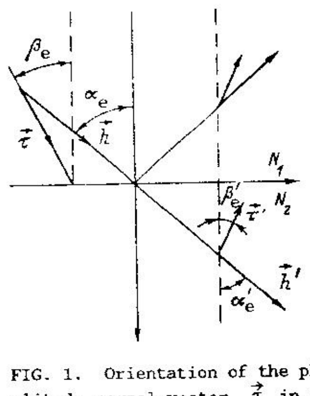

FIG. 1. Orientation of the phase normal vector $\vec{h}$ and the amplitude normal vector $\vec{\tau}$ in the incident, refracted, and reflected waves during the crossing of an interface between media without refraction.

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