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Orientation Dependence of Free-Carrier Impact Ionization in Semiconductors: GaAs

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The dependence of impact ionization rates upon electric-field orientation is demonstrated in GaAs and is related to specific features of the electronic band structure. This effect has profound implications for the interpretation and implementation of avalanche phenomena in semiconductors.

We demonstrate, for the first time, the existence of orientation dependence of impact ionization by free electrons and holes in semiconductors. Experimental evidence for this effect is given with use of GaAs oriented in the ⟨111⟩ and ⟨100⟩ directions. The results can be understood in terms of calculations[1] which show the strong dependence of the energy threshold for impact ionization on the details of the electronic band structure. In particular, for the ⟨111⟩ direction holes have a higher ionization rate than electrons over the range of electric field 6×10^5 V/cm$>E>3\times10^5$ V/cm. In the ⟨100⟩ direction, however, holes have a higher ionization rate than electrons only for electric fields less than 4.5×10^5 V/cm; for electric fields higher than this value, the electron ionization rate becomes larger than the corresponding rate for holes. Because the performance of a device utilizing the avalanche principle (such as an avalanche photodiode) is a function of the ionization rates, there will always exist at least one preferred direction in any semiconductor which optimizes avalance device performance.[2]

Impact ionization can occur in a semiconductor when a free carrier (electron or hole) can gain sufficient energy, such as from acceleration in an electric field, to create an additional electron-hole pair by excitation of an electron from the valence band to the conduction band. It is now recognized that the impact ionization rate for electrons (α) and for holes (β) are in general different, reflecting the different dynamic properties of electrons and holes. It has been shown recently[3] that $\beta>\alpha$ in GaAs with the electric field in the ⟨100⟩ direction for electric fields in the range 3×10^5 V/cm$>E>2.0\times10^5$ V/cm. We have confirmed the basic features of this result in the same range of electric field using a more sophisticated experimental technique which permits separate injection of pure electron and pure hole currents into the high-field avalanche region. We have extended these measurements to electric fields as high as 6×10^5 V/cm, where the behavior of α and β is quite different. We have given a description of this technique and analysis of experimental measurements in earlier work on impact ionization.[4,5]

Baraff has shown[6] that the impact ionization rates depend strongly on the threshold energy for ionization by the initiating hot carrier. Recently, we have demonstrated[1] that these carrier threshold energies are very sensitive to the details of the energy-momentum relationship for the carrier involved. Threshold energies can be calculated from the electronic band structure with use of a method first described by Anderson and Crowell.[7] However, accurate band structures, now available for the entire Brillouin zone from nonlocal pseudopotential calculations,[8] are required for a proper analysis.

The first experimental evidence indicating the strong dependence of the ionization rates upon the electronic band structure was seen in a study[5] of impact ionization in $GaAs_{1-x}Sb_x$ mixed-crystal alloys. Measurements were made for the electric field in the ⟨100⟩ direction. It was observed that lowering the fundamental band gap from 1.45 to 1.2 eV, by addition of 10% GaSb into GaAs, relaxed the conditions on electron-initiated impact ionization to the extent that $\alpha > \beta$, whereas for GaAs $\beta > \alpha$ over the same range of electric field. It is well known that the electronic band structure of semiconductors is direction dependent. However, it has not been previously recognized that the ionization rates for electrons and holes should depend on the orientation of the electric field used to excite carriers to threshold. Nevertheless, it should be clear that the effect of changing the orientation of the electric field on the ionization rates is similar to that of varying the band gap because in both cases the threshold energies are directly affected by such changes. We will now show the experimental measurement of the directional dependence of impact ionization in GaAs, and discuss its relation to the details of the electronic band structure of this compound.

In Figs. 1(a) and 1(b) we plot the difference in the ionization rates, $\alpha - \beta$, as a function of electric field in the ⟨100⟩ and ⟨111⟩ directions, respectively. It is obvious that the two directions are not equivalent for impact ionization. In particular, note that $\alpha - \beta < 0$ in the ⟨111⟩ direction throughout the entire range of the measurement. On the other hand, in ⟨100⟩ GaAs $\alpha - \beta > 0$ for electric fields in excess of 4.5×10^5 V/cm. The peak seen in the ⟨100⟩ direction at highest fields was reproduced in two junctions on one wafer. In very recent data, however, this feature has not been seen in some junctions, although these measurements are otherwise in excellent agreement. Therefore, it is not possible to conclude from these measurements that this peak represents intrinsic hot-carrier behavior in GaAs. However, careful real-time monitoring of the photocurrent established that the peak is not the result of microplasmas. In the ⟨110⟩ direction, additional measurements show that the ionization rate, within the experimental error, is slightly greater than the hole rate over a similar range of electric field, with the difference becoming quite clear at higher fields ($E \gtrsim 5\times10^5$ V/cm).

The determination of ionization rates was made in reverse-biased p-n junctions in which electric fields of the order of 5×10^5 V/cm can be achieved easily. The samples were abrupt p-n junctions fashioned from wafers grown in this laboratory by liquid-phase epitaxy. In all cases, the p side was heavily doped with Ge to $p \cong 2\times10^{18}$ cm^{-3}. The p-layer thicknesses were ~5 μm. The nominally undoped n side had a donor concentration of 1.8×10^{16} cm^{-3} and 8×10^{16} cm^{-3} for the ⟨100⟩ and ⟨111⟩ orientations, respectively. These doping levels were chosen so that the electric field at breakdown would be greater than 5×10^5 V/cm.

Photocurrent multiplication by pure electron injection was achieved by optically generating carriers using 0.6328 μm (above the GaAs band gap at 0.87 μm) radiation on the p side of the junction. Similarly, pure-hole-injection currents were obtained by etching a well in the n-type substrate to within 10 μm of the junction and irradiating the n side of the junction with 0.6328-μm light. A 50-μm-diameter optical fiber was used to confine the light to a small fraction of the junction area while reducing scattered light to a minimum. The photocurrent output of the diode as a function of reverse bias was recorded using synchronous detection techniques. The output was also monitored to insure that the results were not distorted by the effects of microplasmas at high fields.

These experimental conditions allow the straightforward determination of M_e, the electron-initiated photocurrent multiplication, and M_h, the hole-initiated multiplication as a function of reverse bias as has been explained in an earlier work.[4] The impact ionization rates, which give the number of secondary carriers generated per unit length by a hot carrier, can be obtained from the equations

$$\beta = M_e^{-1} d \ln M_h / dW, \tag{1}$$

$$\alpha = \beta + (d/dW) \ln(M_e/M_h), \tag{2}$$

for holes and electrons, respectively, where W is the width of the depletion region in the reverse-biased diode.

The results of Fig. 1 were deduced directly from the measured M_e and M_h by use of Eq. (2). Further analysis of the data, with use of these two equations, yields the ionization rates α and β as a function of reciprocal electric field. We show the results of this analysis in Fig. 2(a) for the ⟨100⟩ orientation of the electric field, and in Fig. 2(b) for the ⟨111⟩ orientation. Within the accuracy for which ionization-rate measurements from different samples can be compared (uncertainty of ~15% in the magnitude of the electric field), impact ionization rates for holes cannot be distinguished in these two orientations. On the other hand, the behavior of the electron ionization rates is seen to be quite different, particularly toward lower fields. For example, at a

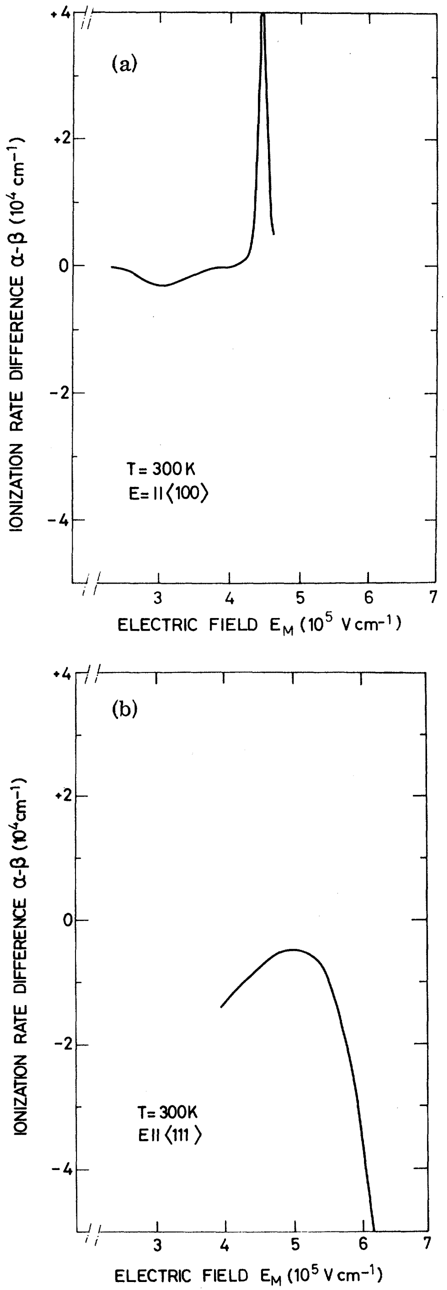

FIG. 1. Difference in the measured impact ionization rates, $\alpha-\beta$, vs the reciprocal peak electric field, E_m^{-1}, in the reverse-biased junction: (a) ⟨100⟩ GaAs, (b) ⟨111⟩ GaAs.

field corresponding to $1/E_M = 3.1\times10^{-6}$ cm V^{-1}, the electron ionization rate in the ⟨111⟩ direction is approximately zero (not shown) whereas in the ⟨100⟩ direction this rate is nearly 2×10^3 cm^{-1}. These differences can be understood in terms of the conduction-band structure for the two orienta-

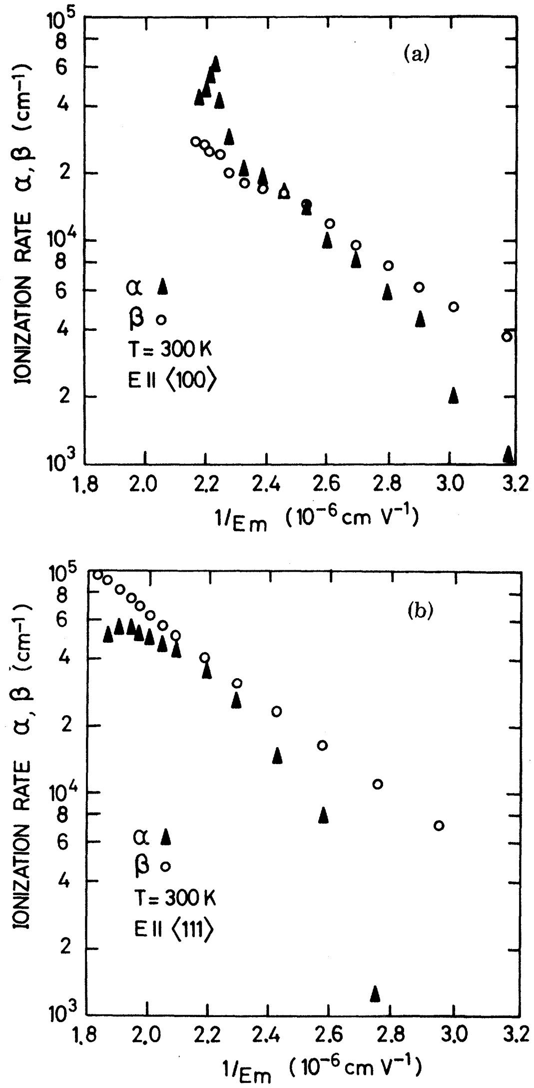

FIG. 2. Measured impact ionization rates for electrons, α, and holes, β, vs reciprocal peak electric field: (a) ⟨100⟩ GaAs, (b) ⟨111⟩ GaAs.

tions.

In Fig. 3 we show the electronic band structure for both the ⟨100⟩ and ⟨111⟩ directions in GaAs.[8] It can be seen that in the ⟨111⟩ direction the energy width of the conduction band is less than the band gap, making impact ionization by electrons in this band ($\Gamma_6 - L_6$) impossible. In order to initiate impact ionization, these electrons must be scattered to another conduction band. In the ⟨100⟩ direction, the lowest conduction band ($\Gamma_6 - X_6$) has an energy width that is larger than the band gap, but the conditions of energy conservation and momentum conservation cannot be

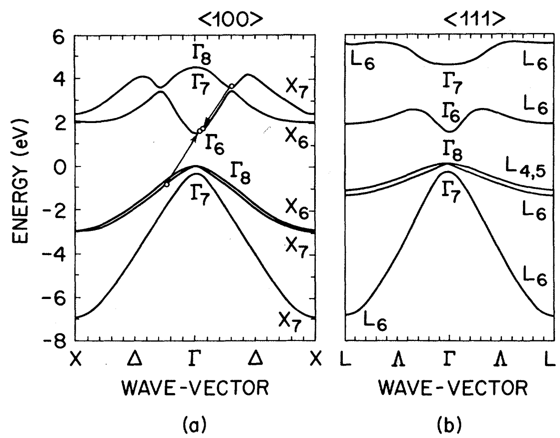

FIG. 3. Electronic band structure in GaAs: (a) ⟨100⟩ GaAs, showing calculated impact-ionization transitions for electron initiation at the lowest energy threshold; (b) ⟨111⟩ GaAs, for which the lowest conduction band is too narrow to perimit electron-initiated impact ionization.

satisfied for an electron-initiated impact-ionization event. However, these two conditions can be satisfied in the next higher band ($\Gamma_7 - X_7$).[7] In fact, the lowest threshold energy occurs for an electron in this band very close to the pseudogap between these two conduction bands at $k_x/k_{\rm max} = 0.3$ (see Fig. 3).[1] The width of this gap is about 0.2 eV.[8] Quantitative analysis of electron-initiated impact ionization thus requires the consideration of tunneling across this gap, or electric-field strengths in the range of our measurements. A calculation based on an uncertainty-principle argument shows, as confirmed by more sophisticated estimates, that the tunneling probability is substantial in this range of fields.[9] Hence electrons in the ⟨100⟩ direction may reach threshold directly while this behavior is strictly forbidden in ⟨111⟩ orientation.

Threshold-energy calculations[1] for $GaAs_{0.9}Sb_{0.1}$ have shown that the lowest threshold energy for impact ionization by electrons lies in the lowest conduction band (near $k_x/k_{\rm max} \simeq 0.26$). The electron is not required to tunnel into the upper conduction band, and for this compound the electron ionization rate is greater than the hole ionization rate even at lower fields, $(2-3)\times 10^5$ V/cm.[5]

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