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RESONANT ENHANCEMENT OF INTRINSIC IMPACT IONIZATION INVOLVING SPIN-ORBIT SPLIT-OFF VALENCE BAND STATES

O. Hildebrand, W. Kuebart, J. Lutz and K.W. Benz

Physikalisches Institut, Teil 4, Universität Stuttgart,
D-7000 Stuttgart 80, Fed.Rep.Germany

The impact ionization coefficients of electrons (α) and holes (β) have been investigated for the $Ga_{1-x}Al_xSb$ system with special emphasis on ionization initiated by holes from the spin-orbit split-off valence band. The experimental data show a resonant enhancement of β by a factor of > 20 at x = 0,065. At this composition, the spin-orbit splitting, Δ, is equal to the bandgap energy, E_g, and the hole threshold energy, E_i, goes through a minimum with $E_i = E_g = \Delta$. In contrast to theoretical expectations, β depends exponentially on the difference between E_i and E_g.

I. Introduction

The present understanding of intrinsic impact ionization is still incomplete. In early theories, the ionization coefficients were derived with classical arguments from carrier distribution functions, calculated from Boltzmann's transport equation [1, 2]. In more recent publications, the quantum mechanical transition probability for the impact ionization process has been included [3]. However, the calculation of ionization coefficients from first principles is very difficult, especially because the exact wavefunctions involved are not known in an electric field.

Experimentally it is well established that the impact ionization coefficients depend on crystal composition, orientation and temperature, i.e. on the bandstructure [4]. These effects have been attributed to changes in the threshold energy E_i for impact ionization. However, no systematic investigation with a controlled variation of the threshold energy has been made up to now. The aim of this paper is to investigate the actual influence of the threshold energy on ionization coefficients. We have choosen an ionization process that allows a pronounced, externally controllable change in E_i, combined with the possibility of an unambiguous identification of the ionization process. The $Ga_{1-x}Al_xSb$ system is ideal for these investigations: The spin-orbit splitting Δ is similar to the band gap energy E_g. For impact ionization initiated by holes from the split-off valence band, occuring near $\vec{k} = 0$, the threshold energy, E_i, depends on the ratio Δ/E_g and goes through a pronounced minimum with $\Delta = E_g = E_i$. This change in E_i can be controlled by the crystal composition or by lattice temperature.

II. Experimental

A series of $Ga_{1-x}Al_xSb$ PIN mesa diodes with $0,6 > x \geq 0$ was prepared from structures grown by LPE on Te-doped GaSb substrates, (100) and (111) oriented. The I-regions were prepared with controlled melt-back during epitaxial growth [5].

The width and position of the i-region was determined with SEM/EBIC measurements, combined with quantitative X-ray analysis to check the compositional homogeneity throughout the space charge region. Since the values of the spin orbit-splitting, Δ, and of the bandgap energy, E_g, depend on crystal composition, x, and lattice temperature, T, we have varied both parameters. $E_g(x,T)$, $\Delta(x,T)$ and the compositional dependences of all masses were obtained from linear interpolations between the respective literature data [6, 7, 8, 9].

For the determination of the ionization coefficients at various values of Δ/E_g (cf. table 1), separate photocurrent multiplication curves were taken with either pure electron or hole injection, using the beam of a SEM, chopped at 1 kHz, as excitation source. With Lock-In processing, a set of electron and hole photocurrent multiplication curves for different values of Δ/E_g was obtained.

Table 1

Δ/E_g	0,7	0,88	1,02	1,04	1,1	1,14
composition (x)	0,28$^+$	0,052	0,052	0,052	0,015	0
Temperature (T)	300 K$^+$	80 K	300 K	320 K	300 K	300 K

$^+$These data were taken from Ref. [10]

III. Results and Discussion

For the calculation of α and β from the photocurrent multiplication curves the well known formulas for PIN diodes were used. The experimental data for α (closed symbols) and β (open symbols) are shown in Fig. (1) with Δ/E_g as a parameter. The electron ionization coefficient α is independent of Δ/E_g, whereas the hole ionization coefficient β shows a strong dependence on Δ/E_g. In Fig. (2) we have plotted β normalized with the corresponding values of α, versus Δ/E_g

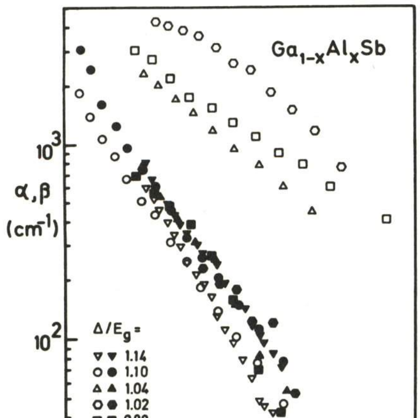

Fig. 1 Experimental data for α and β With different values of Δ/E_g. Open symbols: β, closed symbols: α. All data were taken for (100) orientation, except for $\Delta/E_g = 1,1$ ((111)-orientation)

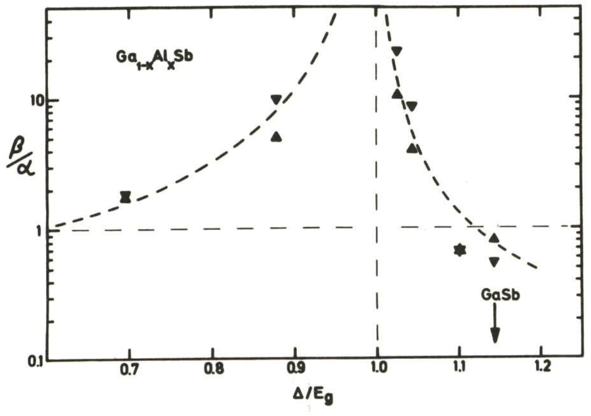

Fig. 2 The ratio β/α as a function of Δ/E_g: This figure demonstrates the resonance of β/α at $\Delta/E_g = 1$. The data at $\Delta/E_g = 0{,}7$ were taken from Ref. [10]

(upright triangles: $E = 4 \times 10^4$ V/cm, inverted triangles: $E = 3{,}3 \times 10^4$ V/cm. $\beta(\Delta/E_g)$ shows a resonant behaviour at $\Delta/E_g = 1$ (corresponding to x = 0.065 at 300 K). This is expected because the threshold energy E_i for impact ionization initiated by holes from the split-off valence band has a pronounced minimum at $\Delta/E_g = 1$: The threshold energy E_i is given by [11]:

$$E_i = E_g\left(1 + \frac{m_{so}(1 - \Delta/E_g)}{2m_{hh} + m_e - m_{so}}\right) \qquad \text{for } \Delta < E_g \qquad (1)$$

and

$$E_i = \Delta \qquad \text{for } \Delta \geq E_g \qquad (2)$$

Thus, at $\Delta = E_g$ it follows that $E_i = E_g$. This is the smallest possible value for any impact ionization threshold energy.

Since in our experiments we have varied E_i in a defined manner, we can compare our complete set of data with the theoretically predicted exponential dependence of ionization coefficients on the threshold energy [3]:

$$\alpha, \beta \sim \exp\left\{ - \frac{E_i}{kT_{eff}} \right\} \qquad (3)$$

Since the "effective carrier temperature", T_{eff}, is not to be expected to depend on Δ/E_g, the slopes of our experimental data (Fig. (1)) should be proportional to the respective threshold energies, calculated from eqs. (1) and (2). In contrast to this expectation, we rather find that the

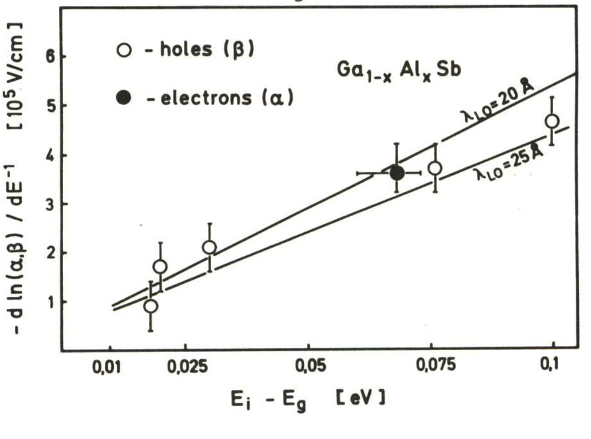

Fig. 3 Slope of the data curves from Fig. (1) versus $E_i - E_g$: This figure does not agree with eq. (3) but implies the validity of eq. (4)

slopes are proportional to the difference $E_i - E_g$ (cf. Fig. (3)). Thus, if we express T_{eff} in terms of Shockley's low field approximation (1), the hole ionization coefficient β can be written as

$$\beta \sim \exp \left\{ - \frac{E_i - E_g}{q\,E\,\lambda_{LO}} \right\} . \qquad (4)$$

With a constant value for the average distance between two carrier-phonon interactions: λ_{LO} = 20 ... 25 Å. It is interesting to note that this value also holds for electrons (black dot in Fig. (1)).

IV. Conclusions

For the $Ga_{1-x}Al_xSb$-System with x ≃ .065, the most effective impact ionization process is the ionization initiated by holes from the spin-orbit split-off valence band: The ionization coefficient β shows a resonance at $\Delta/E_g = 1$, where the corresponding threshold energy reaches the minimum possible value: $E_i = E_g$. The experimental data show an exponential dependence of β on $E_i - E_g$, in contrast to the theoretical expectation.

V. Acknowledgements

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