ON THE INTRINSIC BREAKDOWN OF InSb

E. de Alba
Instituto de Física, Universidad Nacional de México

(Recibido: mayo 13, 1969)

RESUMEN

Usando una generalización de un criterio propuesto recientemente[1] *para la estabilidad de las soluciones de la ecuación de Boltzmann, se demuestra que la ausencia de rompimiento intrínseco en InSb, como se obtiene de algunas teorías recientes*[2,3] *proviene de no haberse introducido cortes en el espectro de fonones.*

ABSTRACT

Using a generalization of a recently proposed criterion[1] *for the stability of the solutions of the Boltzmann equation, it is shown that the absence of intrinsic breakdown in InSb as indicated by recent theories*[2,3] *comes about because no cutoff in the phonon spectra was used.*

I. GENERALIZATION OF THE CRITERION

In a recent article[1] Herrera, de Alba and Martínez have shown that a lower limit to the breakdown critical field can be established without special assumptions about the form of the electron distribution function. In the mentioned article a criterion was established for parabolic bands; in this communication we shall obtain the criteria for a general band and apply them to Kane's hyperbolic band[4] in InSb, with optical polar phonon interaction, in order to establish why no intrinsic breakdown occurs in the calculations for this material[2,3].

According to the criterion, no breakdown is possible if the region of large electron energy in momentum space has an energy content which decreases when the field is applied.

The variation of total energy content is given by

$$\frac{d}{dt}\int E(\mathbf{p})\, f(\mathbf{p},t)\, d^3p = \int E(\mathbf{p})\left[\left(\frac{\partial f}{\partial t}\right)_F + \left(\frac{\partial f}{\partial t}\right)_{Ph}\right] d^3p \qquad (1.1)$$

where $E(\mathbf{p})$ is the band energy as a function of pseudomomentum $\mathbf{p}$. On a right-hand side appear the two terms corresponding to the two mechanisms which can alter the total energy content of the distribution (field F and phonons Ph).

For a field F in the direction Z

$$\left(\frac{\partial f}{\partial t}\right)_{Ph} = -eF\,\frac{\partial f}{\partial p_Z} \qquad (1.2)$$

The energy change due to phonons can be written as:

$$\int E(\mathbf{p})\left(\frac{\partial f}{\partial t}\right)_{Ph} d^3p = \int f(\mathbf{p},t)\left(\frac{dW(\mathbf{p})}{dt}\right)_{Ph} d^3p \qquad (1.3)$$

where $(dW/dt)_{Pb}$, the rate of change in energy of an electron with momentum $\mathbf{p}$, is given by[5]

$$\left(\frac{dW}{dT}(\mathbf{p})\right)_{Pb} = \sum_{\mathbf{q}} \hbar\omega(\mathbf{q}) \left[P_a(\mathbf{p}, \mathbf{p}+\mathbf{q}) - P_e(\mathbf{p}, \mathbf{p}-\mathbf{q}) \right] \tag{1.4}$$

Here $\hbar\omega(\mathbf{q})$ is the energy of a phonon with pseudomomentum $\mathbf{q}$, while P_a and P_e are the probabilities of absorption and emission of a phonon with pseudomomentum $\mathbf{q}$ per unit time.

Using (1.2) to (1.4) in (1.1) we obtain:

$$\frac{d}{dt}\int E(\mathbf{p})\, f(\mathbf{p}, t)\, d^3p = \int f(\mathbf{p}, t) \left[-eF\frac{\partial E}{\partial p_Z} + \frac{dW}{dt}_{Pb} \right] d^3p \,.$$

Hence, according to our criterion, no breakdown is possible if

$$eF < \limsup_{p\to\infty} \left\{ -\left(\frac{dE}{dp_Z}\right)^{-1} \left(\frac{dW}{dt}\right)_{Pb} \right\} \tag{1.5}$$

This expression is valid for any type of band-interaction mechanism. The results are not altered by the existence of interelectronic collisions or assumptions concerning the distribution function.

II. APPLICATIONS TO InSb

According to Kane[4], the energy band in this material is of the form

$$E(\mathbf{p}) = A(\sqrt{1 + Bp^2} - 1) \tag{2.1}$$

where A and B are constants.

The mechanism of scattering is usually assumed to be the interaction with polar optical phonons, in which case

$$P_{\binom{a}{e}}(\mathbf{p};\mathbf{p}\pm\mathbf{q})=\frac{2\pi}{\hbar}\,B(q)\begin{pmatrix}\bar{n}\\ \bar{n}+1\end{pmatrix}\delta(E(\mathbf{p}\pm\mathbf{q})-E(\mathbf{p})\mp\hbar\omega)\,, \quad (2.2)$$

where $B(\mathbf{q})$ is the square of the interaction matrix, of the form[6]

$$B(q)=\frac{1}{\sqrt{q^2}}\,B_p \quad (2.3)$$

and $\bar{n}$ is the phonon number $\bar{n}=\left[\exp\frac{\hbar\omega}{kT}-1\right]^{-1}$. Using expressions (2.1) to (2.3) and (1.4) in the expression (1.5) for our criterion, and assuming no phonon cutoff, one obtains after some integration

$$eF<\lim_{p\to\infty}\frac{B_p\,\bar{n}}{2\Pi\hbar^4A^2B}\,\frac{\sqrt{1+Bp^2}}{Bp^2}\Bigg\{-(\sqrt{1+Bp^2}+C)\times$$

$$\times\, ln\,\frac{\sqrt{(\sqrt{1+Bp^2}+C)^2-1}+\sqrt{Bp^2}}{\sqrt{(\sqrt{1+Bp^2}+C)^2-1}-\sqrt{Bp^2}}+$$

$$+\,e^{\frac{\hbar\omega}{kT}}\,(\sqrt{1+Bp^2}-C)\;ln\left[\frac{\sqrt{Bp^2}\pm\sqrt{(\sqrt{1+Bp^2}-C)^2-1}}{\sqrt{Bp^2}-\sqrt{(\sqrt{1+Bp^2}-C)^2-1}}\right] \quad (2.4)$$

where $C = \hbar\omega/A$. It is easy to see that the above limit is ∞: that is, for no finite applied field does there exist a breakdown, as has been obtained without using a phonon cutoff by several authors[2,3].

On the other hand, if we use a cutoff q_D for the allowed pseudomomenta of the phonons, we obtain

$$eF < \lim_{p \to \infty} \frac{B_p n}{2\pi \hbar^4 A^2 B} \frac{\sqrt{1+Bp^2}}{Bp^2} \left\{ -(\sqrt{1+Bp^2}+C) \times \right.$$

$$\ln \frac{B^{\frac{1}{2}} q_D}{\sqrt{(\sqrt{1+Bp^2}+C)^2-1} - \sqrt{Bp^2}}$$

$$+ e^{\frac{\hbar\omega}{kT}} (\sqrt{1+Bp^2}-C) \ln \frac{B^{\frac{1}{2}} q_D}{\sqrt{Bp^2} - \sqrt{(\sqrt{1+Bp^2}-C)^2-1}}$$

The right-hand side has now a finite limit, so that our criterion becomes

$$eF < \frac{B_p}{2\pi \hbar^4 A^2 B^2} \ln \frac{2 q_D B^{\frac{1}{2}} A}{\hbar\omega}$$

showing the existence of a theoretical intrinsic breakdown in InSb.

The lack of a theoretical breakdown which occurs in some recent calculations appears to be a consequence of the incorrect assumption of an unbounded phonon spectrum.

It is to be noted that for parabolic bands the breakdown appears even without cutoff[7].

REFERENCES

1. Herrera I., E. de Alba and M.A. Martínez, J.Chem. Phys.Solids **29**, 745 (1968).

2. Hammar C. and Meissglas P., Phys.Stat.Sol. **24**, 531 (1967).

3. Matz D., J.Phys.Chem.Solids **28**, 373 (1967).

4. Kane E.O., J.Phys.Chem.Solids **1**, 249 (1957).

5. Paranjape V.V., Phys.Rev. **150**, 608 (1966).

6. Fröhlich H., Adv. in Phys. **3**, 325 (1954).

7. De Alba E. and Warman J., J.Phys.Chem.Solids **29**, 69 (1968).