ESAKI KINK EFFECT IN GRAPHITE

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Introduction

The Esaki kink effect is a phenomenon discovered by L. Esaki[1] on bismuth; the current vs. voltage relation shows a sharp kink at a certain voltage when the specimen is subjected to a transverse magnetic field at low temperatures. The cause of this effect is explained as follows. As shown in Fig. 1, the

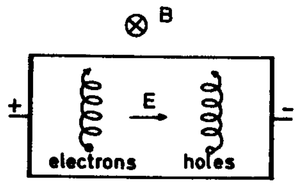

Fig.1 Transverse drift of carriers

electrons and holes drift in the transverse direction if the electric and magnetic fields are applied perpendicularly, as long as the scattering can be neglected. When the drift velocity reaches the velocity of phonons, stimulated emission of phonons begins, hindering the further rise of the velocity of carriers in the transverse direction, thus increasing the current in the direction of the electric field.

In this study we looked for the same effect in graphite, and could clarify a peculiar feature of this material in this effect[2].

Experimental

Since the Esaki effect is a high field phenomenon and the electric conductivity of graphite is rather high, prevention of the temperature rise during the current pulse is important. It was necessary to make the specimen very thin and expose its surface directly to the coolant.

Specimens were prepared from single crystals by cleaving along the basal plane to below one thousand angstroms, cementing to a tip of glass slide and cutting into a four terminal structure under a microscope.

The current-voltage curve was obtained by applying square current pulse of different value to the specimen, and observing the voltage and current on an oscilloscope at a determined time after the start of the pulse. The kink effect needs a finite build-up time; each experimental curve is thus a function of the pulse length.

All experiments were done by dipping the specimen in liquid nitrogen or air, in other words, at about 80 K.

Results

It was found after many runs of experiment that the behavior of the kink effect changes drastically with the carrier mobility.

Fig. 2 shows a typical result of low mobility specimens. Here, the mobility is 1.0×10^4 $cm^2/V{\cdot}s$. In this figure, the two

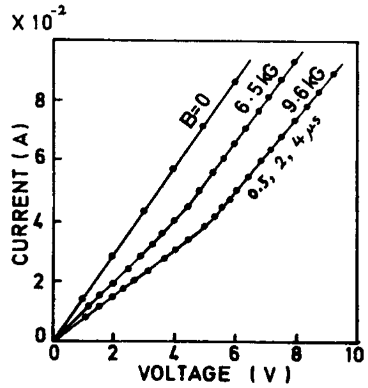

Fig.2 Kinks of a low mobility specimen

curves under the magnetic field have only one kink each, becoming parallel to each other at voltages above the kink, just in the same way as in bismuth.

It is also seen that the curves remain unchanged from 0.5 to 4 μs. This means that the build-up time is quite short, below 0.5 μs.

The velocity of phonons, s, that cause the kink can be calculated as equal to the transverse component of the drift velocity of carriers at the kink as,

$$s = (E/B)/[1 + (\omega_c \tau)^{-2}]$$

where E is the electric field, B the magnetic field, ω_c the cyclotron frequency and τ is the relaxation time of carriers. $\omega_c \tau$ may be determined from the magnetoresistance.

The kink appearing in our low mobility specimens gives on the average 8 km/s as the transverse drift velocity of carriers. This value corresponds roughly to the propagation velocity of transverse lattice vibrations, which is actually 12 km/s in the long wavelength region.

From this result we can say that in low mobility specimens, that is, in defective material, drifting carriers interact strongly with transverse phonons.

Nextly, Fig. 3 represents the results of measurement done on specimens of intermediate mobility. Here, the curves show somewhat complicated behavior.

For a short pulse, 0.5 μs in the figure, there appears a weak kink or the low field kink at first in the course of voltage increase, written as K for the curve of 9.6 kG; then the curves approach straight lines. The point of intersection of the initial ohmic curve and the high field straight line gives the second kink, shown as K' in case of 9.6 kG, which may be called high field kink.

On the other hand, when the pulse is suf-

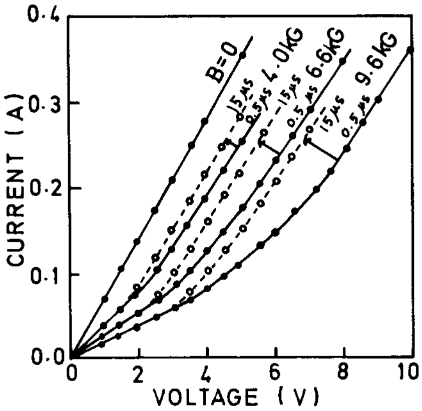

Fig.3 Kinks of an intermediate mobility specimen

ficiently long, 15 μs in the figure, the curves become another set of straight lines starting from the low field kink.

The low field kink in the figure corresponds to the kink in Fig. 2, because the calculated drift velocity has the same value of about 8 km/s, and moreover after a long pulse every curve approaches a fully-developed Esaki curve with a single kink. Therefore, this kink is due to the interaction of carriers with transverse phonons. But the long build-up time indicates that in this material the interaction is weak.

The high field kink, which had to be determined by extrapolation in the above figure, is considered to correspond to the interaction between carriers and longitudinal lattice vibrations; the velocity of relevant phonons was calculated as 17 km/s.

It is to be noted here that the interaction with longitudinal phonons is so strong, that even 0.5 μs pulse is long enough for the full developement of the "high field" kink effect.

Experiments were made then on specimens of highest mobility. Somehow, these specimens broke down easily when the electric field exceeded the high field kink. Anyway, an example is given in Fig. 4. The mobility of this specimen is 2.2 X 10^4 cm^2/V s. As seen in the figure, the low field kink is now very weak. The high field kink could not be studied enough, but lies at around 5.5 V.

It was found incidentally that at electric fields slightly higher than the high field kink in Fig. 4 the change of voltage with time observed on the oscilloscope shows a kind of two-step relaxation as sketched in the same figure.

The hump N appears only in a very limited range of applied current; it moves quickly from right to left with a slight increase of current, disappearing into the initial ringing region. It is apparent that the initial relaxation of voltage is caused by the high field effect, while the second one by the low field effect. The relaxation time or the build-up time of the former effect is judged to be extremely short except in the neighborhood of the high field kink.

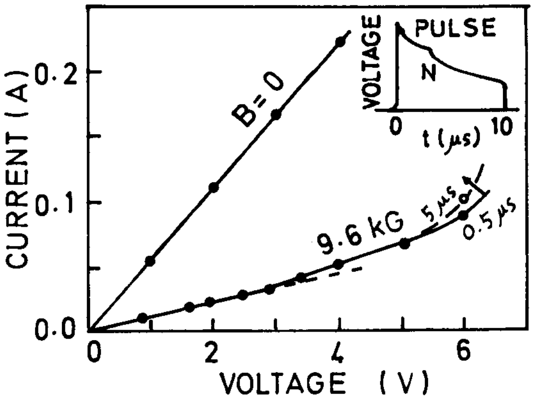

Fig.4 Kinks of a high mobility specimen

Discussion and conclusion

As shown above, in specimens of low carrier mobility, or defective material, the kink effect appears with a short build-up time when the drift velocity of carriers in the transverse direction becomes about 8 km/s. This value agrees roughly with the velocity of transverse lattice vibrations. On the other hand, in crystals of high mobility the above kink or the low field kink becomes weak and needs a long build-up time, while at higher electric fields the other kink comes out with a very short build-up time when the drift velocity reaches about 17km/s, corresponding to the longitudinal lattice vibrations in the basal plane.

Drift velocities of carriers at the kink field are a little smaller than expectation; one reason might be the distribution of the carrier mobility, while another the samllness of the applied magnetic field.

It is concluded that carriers have a strong interaction with longitudinal lattice waves, but if the crystal is defective the interaction with transverse waves becomes also important.

References

1. Esaki L., Phys. Rev. Letters 8,4(1962)
2. Mizushima S. and Fujibayashi Y., J. Phys. Soc. Japan 38,1027(1975)