PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PHYSICS OF SEMICONDUCTORS, KYOTO, 1966
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 21, SUPPLEMENT, 1966

XI-13. Build-up of Phonons in Germanium

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Signals of built-up phonons were observed in rods of relatively pure n-type germanium by detecting microwave signals transmitted through a specimen. The build-up was hardly observed in low resistivity n-type samples and also in p-type samples. When the driving part of sample in electric field was illuminated by a white light, the built-up phonon wave increased with increasing light intensity. In [111] direction the signal amplitude of built-up phonons was the largest. Through these experimentals it is suggested that the existence of the plasma state is of a key importance for exciting the strong phonon wave.

§ 1. Introduction

Phonons can be built-up in CdS, because of its strong piezoelectric coupling. The build-up of phonons in Ge has never been reported, but it may be quite interesting problem theoretically and experimentally, whether phonons can be built-up in Ge, Si and other semiconductors.

This is the first report to observe experimentally the build-up of phonons in Ge. One half of a sample (driving part) has two large area contacts and the remaining half (detection part) has no electrode. When an electric field is applied between two contacts of the driving part, the built-up phonons travel into the detection part and decrease the mobility thereof. This change in mobility is measured by observing microwave signals transmitted through a tapered waveguide if the detection part of the sample is inserted in this tapered waveguide (the driving part is outside of the guide).

The phonons are hardly built-up with increasing impurity concentration in the n-type sample (res. $< 1\Omega$-cm) and also in a p-type Ge at room temperature. If the driving part of sample is illuminated by the white light, the build-up of phonon increases with increasing light intensity, but illuminating the detection part, the built-up phonon wave decays quickly.

The build-up of phonons is also dependent on the crystallographic orientation, and it is the strongest in the direction of [111].

The theoretical explanation for these observed phenomena will be left to the future investigation.

§ 2. Experimentals

1) Method of detection

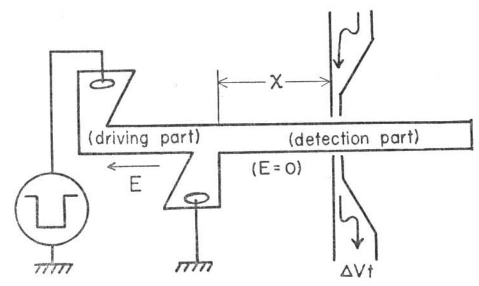

Fig. 1. Method of detection of built-up phonons.

A specimen had two parts, as shown in Fig. 1: one was the driving and the other the phonon-detecting part. In order to avoid contact effects, the driving part had two large area contacts and the remaining half, the detection part had no electrode. When an electric field was applied between two contacts of the driving part, phonons built-up in the driving part travelled into the detection part and decreased the mobility thereof. This change in mobility was measured by observing microwave signals transmitted through a tapered waveguide (the height of 1 mm) into which the detection part of the sample was inserted.

The velocity of built-up phonons propagatin- in the detection part was directly measured by the microwave Doppler effects or by using two tapered waveguides.[1)]

In Fig. 2 is shown the distribution of the change of transmitted μ-wave power corresponding to the decrease of mobility at a reference position in the detection part. This decrease in mobility is possibly caused by the built-up phonons transmitted from the driving part because there existed no electric field in the detection part. The build-up of phonons was usually observed in the direction of drift of electrons. Then, in the following, the experiments were done towards the drift direction of electrons.

2) *Type and conductivity of specimens*

The phonon build-up was easily observed in samples of nearly intrinsic *n*-type germanium, but in low resistivity *n*-type samples with high carrier density and in *p*-type samples the build-up was hardly observed. The change of conductivity or mobility in the detection part can be estimated from the transmitted μ-wave signal as described in a previous paper, and it is shown in Fig. 3 as a function of the driving electric field strength with parameter being temperature.

The change of mobility in the detection part

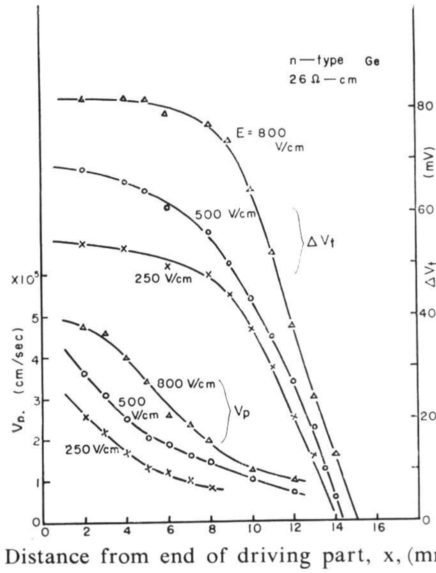

Fig. 2. Distributions of signal amplitudes (ΔV_t) of built-up phonon and its velocity (v_p) along the length of the detection part with parameter being the driving electric field strength.

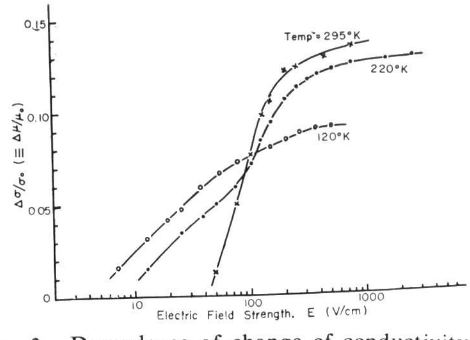

Fig. 3. Dependence of change of conductivity or mobility on electric field strength, with parameter being temperature.

increased with increasing the driving electric field strength. In a lower temperature the mobility changed at lower electric field strength, meaning that phonons can be built-up in a lower field strength and that phonons can travel more easily along the length of the sample.

3) *Decay and velocity of phonon wave*

The mobility change is the larger, the nearer the reference position is from the driving part, and the decrease in mobility increased with increasing the driving electric field strength.

The velocity of phonons in the detection part is also shown in Fig. 2. The velocity decreased with increasing the distance from the end of the driving part, and it increased with increasing electric field strength.

In Fig. 4 is shown the simultaneous recording of the front of phonon waves travelling along the axis of sample at two positions, in which we see the time lag apparently in two signals.

The change of the velocity of phonon flow with the driving electric field strength is shown in Fig. 5. In low electric field strength, the velocity of phonon wave was proportional to the electric field strength, but in high electric field it saturated to nearly the sound velocity in Ge. The increase of the velocity of phonon flow with increasing drift velocity of carriers may be explained by the carrier drag effect.

4) *Illumination by light*

Illuminating the driving part by a white light,

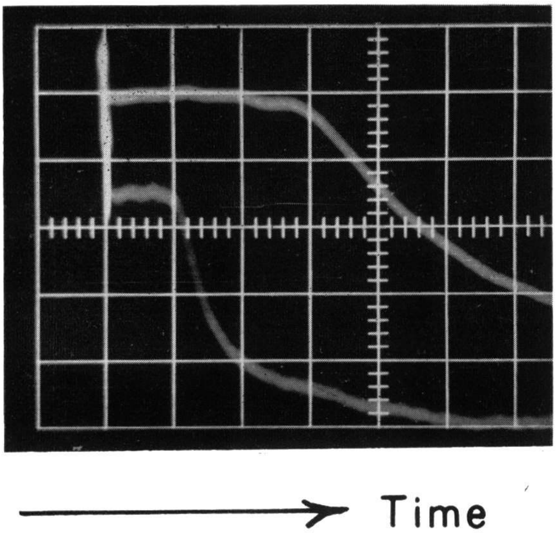

Fig. 4. Simultaneous recording of the front of built-up phonon waves at two positions of 2 and 5 mms of x. Vertical: 10 mV/div. Horizontal: 0.5 μsec/div.

the amplitude of built-up phonons increased with increasing light intensity. The result is shown in Fig. 6. However, illuminating the detection part by the white light the transmitted built-up phonons decreased fairly with increasing light intensity. The result is also in the same figure.

5) *Crystallographic orientation*

The build-up of phonons is dependent on the crystallographic orientation. The studies were done in three directions of [111], [$\bar{2}$11] and [0$\bar{1}$1], which were orthogonal each other. In the [111] direction the signal of built-up phonons was the largest, and in [0$\bar{1}$1] it was hardly observed.

When the detection part of the sample was wetted with de-ionized water, the built-up phonons travelled with a smaller attenuation.

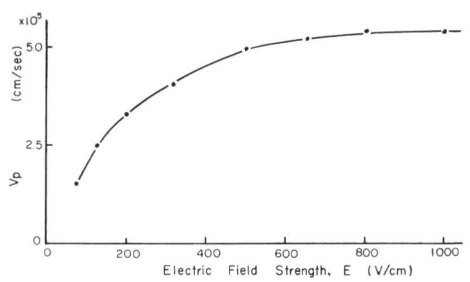

Fig. 5. Dependence of velocity of the phonons (v_p) on the drifting electric field strength at $x=2$ mm.

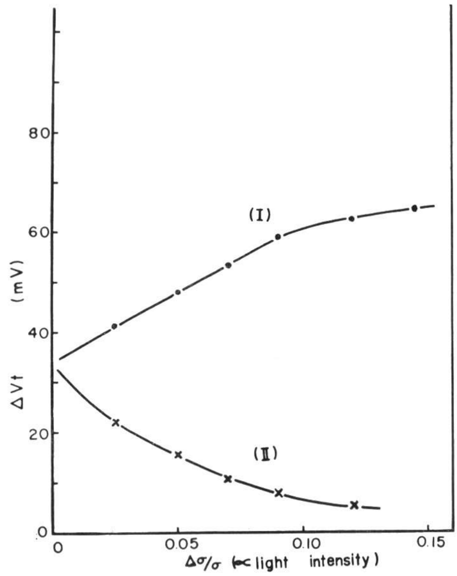

Fig. 6. Changes of signal amplitude ($\varDelta V_t$) with increasing light intensity, when the driving part was illuminated (I) and when the detection part was illuminated (II).

§ 3. Discussions

The recombination of electron-hole plasma in Ge involves three processes of (a) radiative recombination, (b) Auger type recombination and (c) phonon emitted recombination, but the radiationless recombination rate of type (c) in Ge may be fairly large. In Fig. 7 are shown

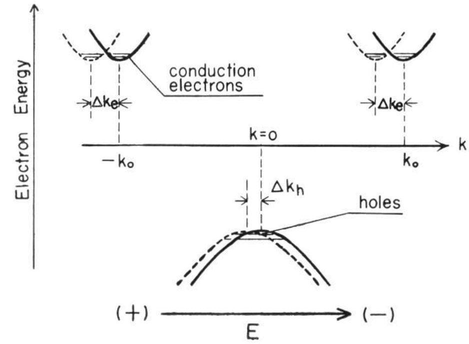

Fig. 7. Band structure of Ge in electric field.

the energy bands of Ge, in which the wave numbers of conduction electrons and holes, k_e and k_h are shifted by $\varDelta k_e$ and $\varDelta k_h$ in the presence of the electric field from the stationary values. $\varDelta k_e$ and $\varDelta k_h$ are given by

$$\varDelta k_e=\frac{eE}{\hbar}\tau_e\,,\quad \varDelta k_h=\frac{eE}{\hbar}\tau_h\,, \tag{1}$$

where E is the electric field strength, and τ_e and τ_h are the relaxation times of electron and hole, respectively. In Ge $\varDelta k_e$ is larger than $\varDelta k_h$.

When drifting electron-hole plasmas recombine by accompanying emissions of phonons, the potential energy of electron, E_g is transformed to energy of phonons with conserving momentums, and E_g is given in multi-phonon process by

$$E_g=N\hbar\omega\,, \tag{2}$$

where N is number of emitted phonons with angular frequency of ω. Electrons in left (+) side emit phonons with wave vector of $(-k_0-\varDelta k_e+\varDelta k_h)$, and electrons in the right (−) side emit phonons with wave vector of $(k_0-\varDelta k_e+\varDelta k_h)$. These emitted phonons may collide dominantly through three phonon normal process with other phonons including thermally equilibrium phonons. Then, the phonons shall gain the average momentum of $(-\varDelta k_e+\varDelta k_h)$ from carriers drifting in electric field.

The velocity of phonon flow, v_p may be related with the drift velocity of carrier, $v_d(\propto E)$, and is given by

$$v_p = \frac{1/\tau_{pr}}{1/\tau_{pp}+1/\tau_{pb}+1/\tau_{pr}} aE\,, \qquad (3)$$

where a is a constant, and τ_{pp}, τ_{pb} and τ_{pr} are the relaxation times of phonons for phonon-phonon collision, phonon-boundary and phonon-enhanced phonon collision, each of which is generally dependent on temperature and wave number of a phonon. The phonon flow moves in the drift direction of electrons because Δk_e is larger than Δk_h. In crystals free from phonon emission phonons are strictly obeying to the Planck's distribution, but the phonon system combined with electron-hole plasma may be deviated from the distribution at thermal equilibrium. In this case $1/\tau_{pr}$, the collision rate of phonons with enhanced phonons due to recombination of plasmas, may be large comparing with $(1/\tau_{pp}+1/\tau_{pb})$.

Figure 5 shows that the relation of eq. (3) is supported qualitatively by the experimental results in a relatively low electric field strength. As the phonon flow cannot be accelerated beyond the sound velocity, the velocity should be saturated to the sound velocity in high electric field strength. Thus the amplitude of phonon wave may increase with increasing electric field strength due to the superposition of the in-phase phonons propagating in sound velocity.

The experimental evidences that the build-up of phonons was quite easy in the nearly intrinsic sample, and that the signal amplitude of built-up phonons increased if the driving part was irradiated with increasing light intensity, suggest strongly that the existence of the plasma state is of a key importance for exciting the strong phonon wave because of its large recombination rate. Furthermore, the fact that the built-up phonons were damped when the detection part was illuminated by the increasing light intensity, suggests that the enhanced phonons caused by the recombination make the travelling phonon wave attenuate.

The signal amplitude of phonon wave was the largest in [111] direction. This is an indication for that the built-up phonons were dominantly optical phonons, because optical phonons in Ge are the most dominant along the [111] direction.[2] These built-up phonons of optical mode may be transformed to the acoustic phonons, because along this direction the process of optical $(o) \rightleftarrows$ acoustic $(a)+$acoustic (a) occurs easily due to the largest value of wave number of emitted phonon by recombination.[3].

When the sample is slightly covered with a liquid, the built-up phonons seem to travel without diffused reflection at the irregular boundary of the solid along the length of sample.

References

1) T. Arizumi, M. Umeno and S. Iwai: Japan. J. appl. Phys. 4 (1965) 861.
2) W. A. Harrison: Phys. Rev. **104** (1956) 1281.
3) J. M. Ziman: *Electrons and Phonons* (Oxford Press) p. 144.

DISCUSSION

Queisser, H. J.: In this context one should mention phonon transmission measurements in Si by K. Hubner (see Exeter Conf.) and later also done on Ge. Here one had a dispersion and also a clear exponential decay with distance of the "relevant phonons" being transmitted and detected. In such measurements one has to be careful that one does not measure trivial thermal effects. What precautions did you take not to measure mobility reduction simply caused by a heat pulse from the driver input?

Umeno, M.: We usually used pulses of short duration to avoid the thermal effect and furthermore if we change the polarity of electrodes, we cannot observe the build-up of phonons. This shows that the mobility reduction by the thermal effect is negligible.