Drift Velocity of Electron-Hole Cloud in Ge at High Electric Field

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(Received September 11, 1978)

The drift velocity of an electron-hole (plasma) cloud in Ge at high electric field was measured at room and lower temperatures by using microwave transmission technique and Doppler method. The drift velocity of the plasma cloud in a nearly intrinsic Ge saturated at a constant value of about 5×10^5cm/sec at sufficiently high electric field. In a lower temperature it begins to saturate at lower electric field. In the high field the build-up of phonons was also observed.

This saturation phenomena of the drift velocity of a plasma wave is related with the build-up of phonons caused by the interaction between electrons and holes in high electric field.

1. Introduction

The drift velocity of electron-hole (plasma) cloud is determined by the ambipolar drift mobility[1], differing from the drift velocity of an individual carrier. Especially in high electric field it behaves in remarkably different manner from that of the hot carrier. The drift velocity of a carrier is rather easily obtained by measuring simply the conductivity as a function of the electric field strength.[2]

The authors discussed in detail theoretically and experimentally the basic principle to detect the motion of the density cloud by applying microwave techniques.[3-4] One way using Doppler method to measure the drift velocity of the density cloud was presented in a previous paper.[3]

In this paper is described the application of the principle for measuring the drift velocity at high electric field and for detecting the signal of built-up phonons. The most important results are that the drift velocity of the density cloud in nearly intrinsic Ge, produced by pulsive injection, saturates at a constant value of about 5×10^5cm/sec at high electric field, and that phonons are strongly built-up, being accompanied with the saturation of the drift velocity.

The saturation phenomena are discussed by the built-up excess phonons due to the increase of electron-hole interaction.

2. Experimental Procedures

The essential part of the experimental arrangement is shown schematically in Fig. 1. Two tapered waveguides were closely set in parallel and a semiconductor rod was inserted perpendicularly through small holes to two waveguides. When a cloud of electron-hole plasma was drifting along the rod, the microwave powers modulated by the local change in conductivity of the rod were simultaneously displayed on a dual beam synchroscope. Therefore the transit time of injected excess carriers was detected by measuring the time delay between both signals.

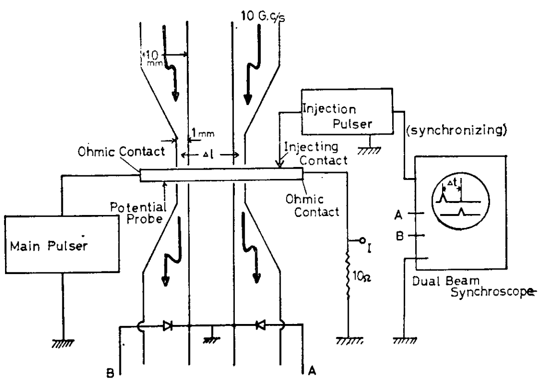

Fig. 1 Block diagram for the measuremet of drift velocity by using two tapered waveguides.

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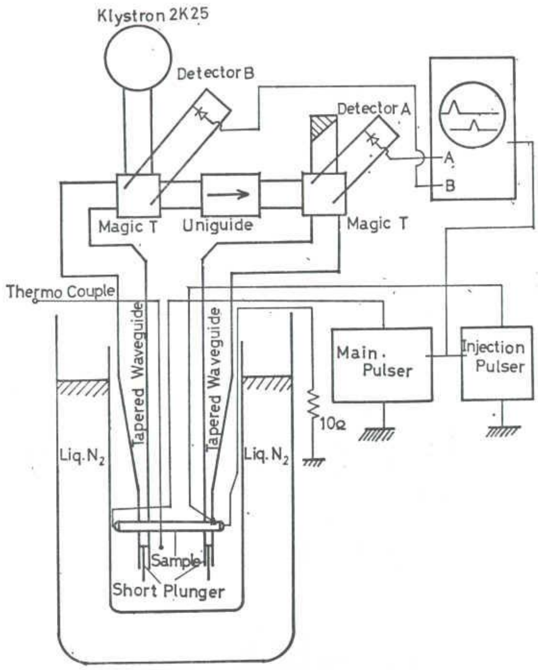

Fig. 2 Method of drift velocity measurement at low temperature.

For the measurement at a lower temperature the apparatus must be modified in such a way as shown in Fig.2. A semiconductor rod was set at the end of two tapered waveguides and both microwave powers reflected from the sample were detected through two Magic-Tee junctions.

Figure. 3 shows the experimental arrangement using three tapered waveguides to detect the built-up phonons. For this purpose the sample was fabricated in such a manner as to accelerate the plasma in one half of the sample (driving part). Another half (detection part) has no electrode and this half was inserted through the third tapered waveguide. When an electric field is 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.[5] This change of mobility was measured by observing microwave signals transmitted through the third tapered waveguide. In the arrangement of Figure 3, the density wave of electron-hole pairs travels from the right (positive (earth) electrode) to the left sides (negative one), but the excess phonons (in the detection part) travel in the opposite direction.

Specimens were mainly n and p-type Germanium of resistivity of about 25Ωcm at room temperature. The dimension of samples was 25mm in length and $1.2\times 1.2\text{mm}^2$ in cross section. Samples cut along ⟨III⟩ direction were lapped mechanically and polished chemically with CP-4 etchant. Ohmic contacts to the n-type sample were alloyed with Pb-10%Sb at 650°C and an injecting contact of small area was prepared at a distance about 2mm from one end. In p-type Ge, ohmic contacts were alloyed with In-5% Ga.

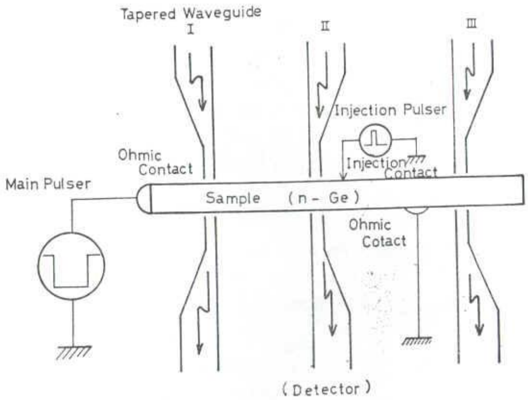

Fig. 3 Method for detecting signals of built-up phonons with drift velocity measurement.

3. Experimental Results and Discussions

In Fig.4 is shown the detected signals of microwave transmitted through a sample on a dual beam synchroscope. The time interval between two signals, caused by the excess conductivity of injected carriers, decreased with the increase of terminal voltage. The drift velocity is calculated by $V_d=\Delta l/\Delta t$, where Δl is the distance between two tapered waveguides and Δt is the time interval during which a density cloud travels the distance Δl. The injected carrier density

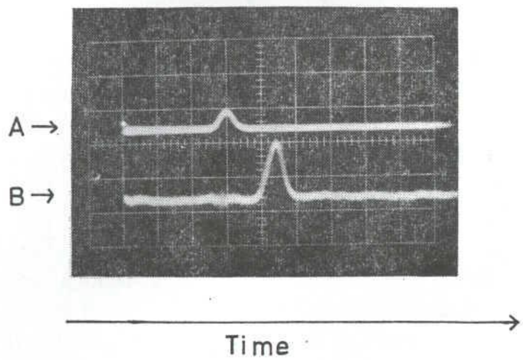

Fig. 4 Simultaneous observation of transmitted microwave signals by using two tapered waveguides. The vertical scale is 5mV/div. and the horizontal 2μsec/div.

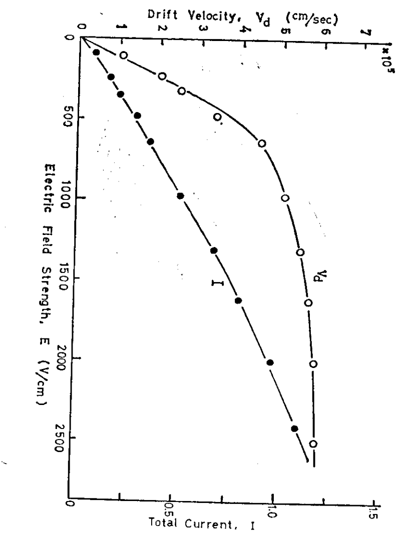

Fig. 5 Dependences of drift velocity and total current on electric field strength, N type 25Ωcm Ge, at 295°K.

was not so large, then the reduction of electric field strength acting on the density cloud was negligibly small. In Fig. 5 is shown the drift velocity against electric field strength for n type Ge at 300°K.

At low electric field the experimental drift velocity is equal to the ambipolar drift velocity, given by $V_d=[\mu_e\mu_h(n_o-p_o)/\mu_e n_o+\mu_h p_o]E\equiv\mu_a E$, where μ_e and μ_h are mobilities of electron and hole, and n_o and p_o their densities, respectively. However, the velocity begins to deviate from the straight line of $V_d=\mu_a E$ at higher electric field strength, and finally it approaches to a constant value of the order of 10^5cm/sec, which is nearly equal to the sound velocity in Germanium. On the other hand, the total current through a specimen deviates slightly from the Ohm's law, but it does not saturate in our experimental range.

At lower temperatures this behaviour became remarkable, as shown in Fig.6: the drift velocity began to saturate at a lower electric field strength. Since both mobilities μ_e and μ_h at a lower temperature are large: than those at room temperature, the ambipolar mobility becomes larger with decreasing temperature. So, the drift velocity should increase at lower temperatures, consisting with the experimental results.

Fig. 7 shows the corresponding total current for the same sample. This curve resembles the hot carrier effects in exstrinsic semiconductors observed by many workers.[2)]

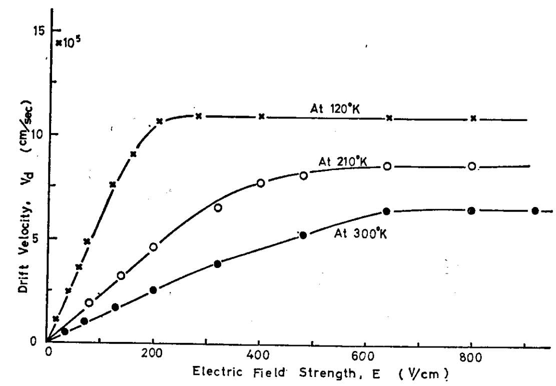

Fig. 6 Dependence of drift velocity on electric field strength at various temperatures, N type 25 Ωcm Ge.

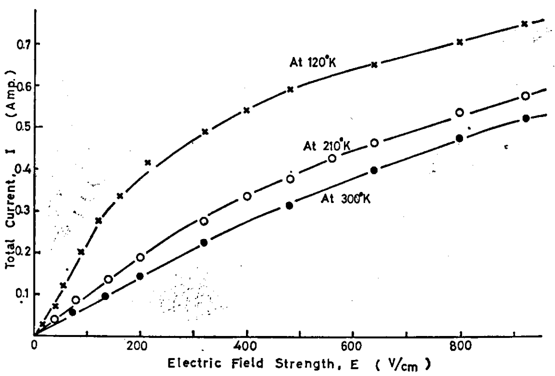

Fig. 7 Dependence of total current on electric field strength at various temperatures, N type 25 Ωcm Ge.

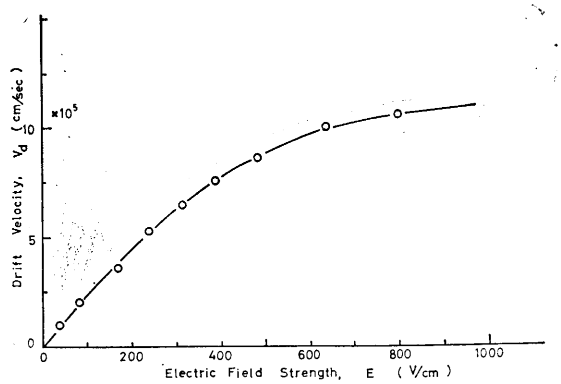

Fig. 8 Dependence of drift velocity on electric field strength, P type 30Ωcm Ge, at 300°K.

As shown in Fig.8 the drift velocity of a p-type Ge behaves similarly but the deviation from the ambipolar velocity moves to a higher field side, and also the saturation velocity becomes larger (1.2×10^6 cm/sec).

The above-mentioned results suggest that the density cloud of electrons and holes interacts strongly with phonons. Really, signals of built-up phonons were detected when the drift velocity began to saturate.

When an electric field was applied between two contacts of the sample shown in Fig.3, the microwave powers transmitted through the part free from electric field (the detection part) were modulated, corresponding to the decrease of conductivity. Surely this decrease of conductivity does not come from the reduction of carrier density but from the reduction of mobility.[5]

This signal travelled along the axis of the detection part with a velocity near the sound velocity, but it needs more careful and precise experiment to know whether this velocity is exactly equal to the velocity of a density cloud or not. Excess phonons built-up in the driving part travelled into the detection part and reduced the mobility of the reference position.

At a lower temperature phonons were buit-up in a lower electric field strength,[5] in the same fashion as described on the drift velocity at a lower temperature.

When the specimen was illuminated uniformly with a white light, the amplitude of signal of built-up phonons became large, and the drift velocity decreases with increasing light intensity, as shown in Fig.9. In this case the ambipolar mobility is given by

$\mu_a=\mu_e\mu_h(n_o-p_o)/\mu_e n_o+\mu_h p_o+\Delta p(\mu_e+\mu_h)\equiv e\mu_e\mu_h(n_o-p_o)/\sigma$, where Δp is the density of excess electrons and holes (excess plasma) produced by illumination, and σ is the conductivity under illumination.

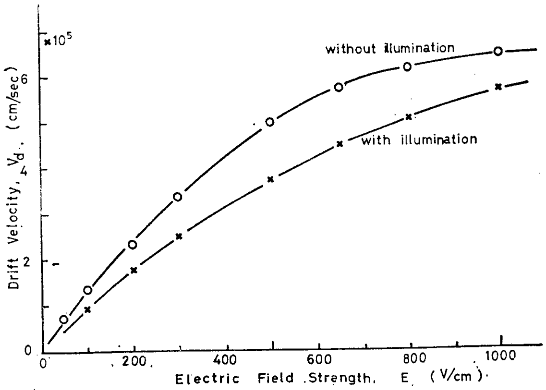

Fig. 9 Dependence of drift velocity on electric field strength with and without illumination, N type 26Ωcm Ge, at $290°$K.

In Fig. 10 $(\mu_a\sigma)$ is plotted as a function of the light intensity in terms of $\Delta\sigma/\sigma_o$, where μ_{ao} and σ_o are the ambipolar mobility and conductivity without illumination. This figure indicates that the value of $(\mu_e\mu_h)$ decreases with the increase of light intensity, because (n_o-p_o) is constant.

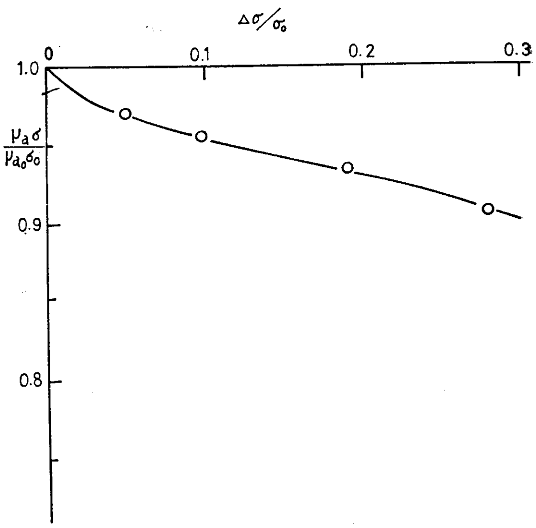

Fig. 10 Change of $(\mu_a\sigma)$ with intensity of illumination $(\Delta\sigma/\sigma_0)$.

At room temperature and at low electric fields the electron-hole scattering is negligibly small in Ge containing carrier density of about 10^{14}cm^{-3}.[6] However, in the presence of high density of electron-hole pairs (plasmas) the interaction between electrons and holes increases in proportion to the excess carrier density. Especially at higher electric field, many phonons may be created through the interaction or the recombination between electrons and holes.[5] Thus built-up excess phonons decrease the mobilities of individual carriers, μ_e and μ_h with increasing electron-hole pair density. But the saturation of the drift velocity is not explained by the reduction of mobilities of electron and holes. Possibly, it is indispensable to consider the collective motion of the electron-hole plasma cloud in the field of built-up and travelling excess phonons.[7,8]

The authors are grateful to Miss M. Sakamoto for her assistance.

This work was partially financed by the Scientific Research Fund of the Ministry of Education.

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