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Measurement of Avalanche Multiplication in Germanium P-N Junctions

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Abstract

An advanced experimental method is described for the measurement of multiplication factor of holes in germanium. The method utilizes *pnp* transistors to inject holes from the emitter and employs a triangular wave as the reverse bias to eliminate the internal heating of the devices. Some results obtained are also presented.

I. Introduction

Various investigations and experiments have been done on the avalanche effects of semiconductor *p-n* junctions, especially of both germanium and silicon, since the first report of MeKay and McAfee [1].

In the investigation of avalanche effects, the most important parameter which can be experimentally obtained is the multiplication factor M because it determines the breakdown voltage of *p-n* junctions.

The avalanche breakdown voltage of *p-n* junctions can be calculated as a function of the resistivity of a starting material by the avalanche theory. The breakdown voltages of actual junctions have often been less than expected by the theory and moreover the breakdown characteristics have often been neither stable nor smooth. These effects have been explained by the defect structure in the junctions. The so-called microplasmas have been thought to be caused by imperfections in the crystal lattice.

The multiplication factor is promising parameter to study the influence of the defect structures on breakdown characteristics of *p-n* junctions. The usual way of measuring M is to observe the multiplication of initial carriers injected into a reverse biased *p-n* junction. There are three ways to inject initial carriers i. e., illumination of light, bombardment of alpha particles and minority carrier injection

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[1] K. G. McKay and K. B. McAfee, Phys. Rev., 91, 1079 (1953).

from the emitter of a transistor structure.

The present paper describes an advanced experimental method to obtain the multiplication factor of holes injected from the emitter into the collector junction of alloyed germanium *pnp* transistors. The emitter junction is driven forward by an *ac* voltage to inject holes and their multiplied current is measured as a function of reverse bias.

Another important feature of this experimental method is the use of triangular wave of short duration and of long interval as reverse bias. With this technique, the difficulty due to internal heating of the junction which often distorts *V-I* characteristics in the breakdown region can be fairly eliminated. It is possible to observe a single trace of *V-I* characteristics with and without injection simultaneously on an oscilloscope.

This method has an advantage over photo-injection method in simplification of the experimental arrangement and is preferable in the low-temperature measurement.

Multiplication factors and *V-I* characteristics of several alloyed *pnp* transistors which contain microplasmas have been obtained with this method at 78°K. The multiplication factors obtained are very analogous to those of silicon *p-n* junctions with photo-injection method[2] and it shows the validity of this method.

Dependence of *V-I* characteristics on the duration, interval and steepness of triangular wave has been also studied that which proves that *dc* measurement is not suitable for the observation of avalanche effects.

II. Experimental Method

The principle of measuring M is the same as that of alpha α (current amplification factor of common-base configuration). Initial carriers (holes) are injected from the emitter junction and then multiplied in the depletion region between the base and the collector under certain reverse bias. α is defined as the ratio of the collector current I_c to the emitter current I_e. Theoretically α can be expressed by the equation

$$\alpha = \gamma \beta M$$

where γ = emitter efficiency, β = base transport efficiency.
When both γ and β are independent to the collector voltage V_c, the increase in the collector current I_c with the increase of V_c is only due to M. Hence, M can be evaluated by the relation

$$M = I(V_c)/I$$

where $I(V_c)$ is the increment of the collector current I_c by the multiplication at a given voltage V_c, and I is the increment of I_c at low voltage where M is equal

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[2] R. L. Batdorf, et al., J. Appl. Phys., 29, 1103 (1960).

to unity. In such a three terminal measurement of M, the preferable method is to maintain the emitter current constant to make the injected current independent to the applied collector voltage.

In this method, the emitter junction is driven by *ac* current source for the detection of the increment of the collector current due to multiplication.

The principle of the measurement is shown schematically in Fig. 1.

In Fig. 2, is also shown the schematic drawing of the measuring units.

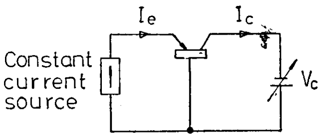

Fig. 1. Principle of the measurement.

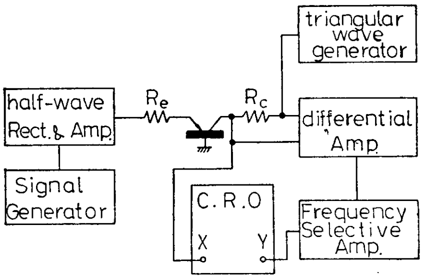

Fig. 2. Schematic drawing of the measuring circuit.

In Fig. 2, the emitter voltage supply consists of a signal generator and a silicon diode, that produce rectified halfwaves which drive the emitter through a high resistor R_e. To maintain the emitter current constant, the value of R should be the larger the more desirable. For the actual value of R_e, over 500 KΩ is sufficient for approximation of constant current.

In order to avoid internal heating of the test devices, the collector junction is biased by triangular wave voltage of short duration. Its duration and interval and output voltage can be widely changed.

The collector currents are detected across the series resistor R_c by a differential amplifier of which output is led to the *Y*-cordinate of an oscilloscope directly in case of the measurement of *V-I* characteristics. In measurement of multiplication characteristics, the output of the differential amplifier is put to a frequency selective amplifier with adequate bandwidth tuned at a frequency of the emitter driving signal. Subsequently the filtered signal is led to the *Y*-cordinate. The collector voltage is led to the *X*-cordinate of the oscilloscope after being picked up by a high-impedance probe. Thus both *V-I* and multiplication characteristics can be displayed on a screen of the oscilloscope.

In the breakdown region, there is a certain possibility of internal heating of the device, furthermore, the breakdown characteristics of *p-n* junctions have been found to be considerably affected with heat. Internal heating is caused by power dissipation of the device. The power dissipated during one duration of the triangular wave can be proportional to the current flowing in the breakdown region because the current is very small below the breakdown region and also in the breakdown region, the internal resistance of *p-n* junctions becomes considerably small. Hence, the peak collector current during one duration of the triangular wave should be kept under a certain value to avoid internal heating. Heat generated during one duration of the triangular wave is dissipated at its recess period i.e. its interval. So the duration and the duty ratio of the triangular wave should be chosen carefully with due consideration of the thermal time constant of the test devices. Actually the peak collector current, the interval and the duration have been determined by experiments. The triangular wave of 10 μs ~ 20 ms duration and of 1 ms ~ 1 s. interval has been used.

The series resistor R_c should be kept so small that the current waveforms may not be affected by stray capacities in the circuit. The adequate value of R_c is limited by these stray capacities and the signal-to-noise ratio of the measuring apparatus.

III. Results

For the multiplication measurements, good results have been obtained with R_c of 2 KΩ ~ 10 KΩ and with the emitter driving signal of 100 KHz ~ 250 KHz.

To study the effect of internal heating on the breakdown characteristics and to determine adequate value of the peak collector current interval and duration, the dependence of the breakdown voltage V_B on these three factors has been observed. Typical results are shown in Fig. 3 and Fig. 4. In Fig. 3, are shown the curves for breakdown voltage *vs* interval of the triangular wave for different values of the peak collector current. The breakdown voltage *vs* the peak collector current I_p for different intervals of the triangular wave are also plotted in Fig. 4.

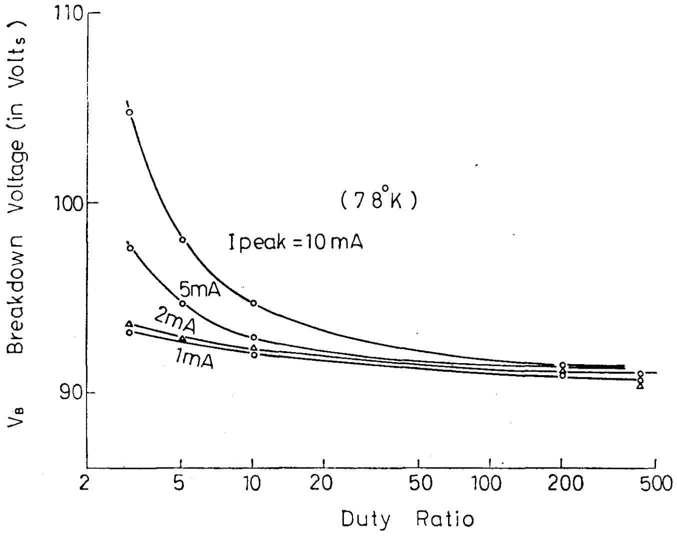

Fig. 3. Depedence of the breakdown voltage on duty ratio of the triangular wave for different peak collector currents. Their duration is 1 ms.

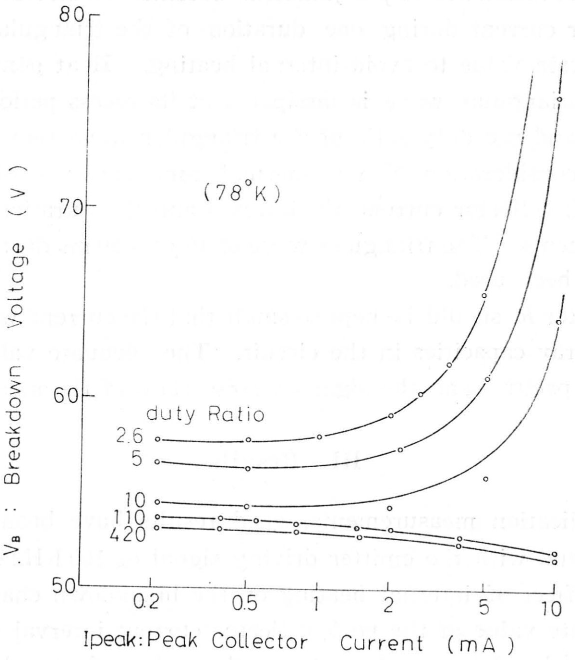

Fig. 4. Dependence of the breakdown voltage on the peak collector current for different duty ratio. Their duration is 1 ms.

From these results it is concluded that the breakdown voltage increases according to the increases of I_p and to the decrease of the interval, that apparently shows the effect of internal heating of the device. These results also show that duty ratio over 50 and I_p less than 10 mA are preferable to avoid the effect due to internal heating.

Typical results of both multiplication and breakdown characteristics for convenient alloyed germanium transistors by this method are shown in Fig. 5, 6 and 7.

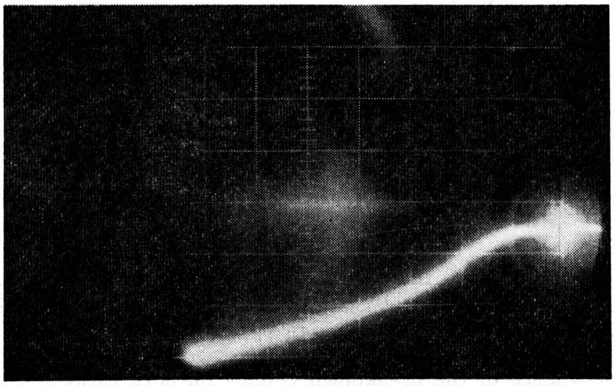

Fig. 5a. *V-I* characteristic called "soft" breakdown. V : 1 mA/cm, H : 10 V/cm.

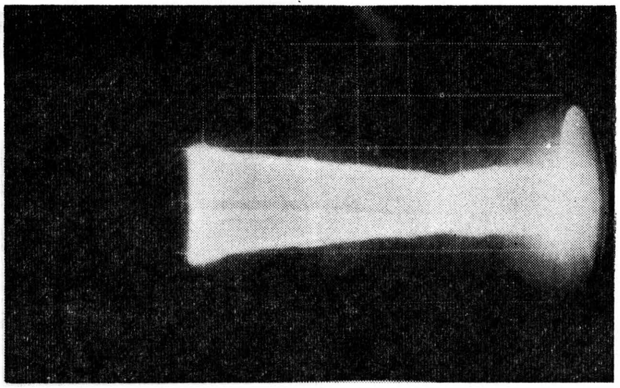

Fig. 5b. Multiplication characteristic of a transistor shown in Fig. 5a.
H : 10 V/cm, Injection level 100 μA.

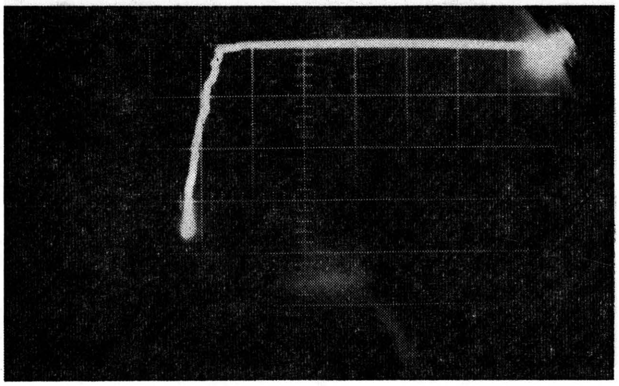

Fig. 6a. *V-I* characteristic of a transistor with a negative resistance.
V : 1 mA/cm, H : 10 V/cm.

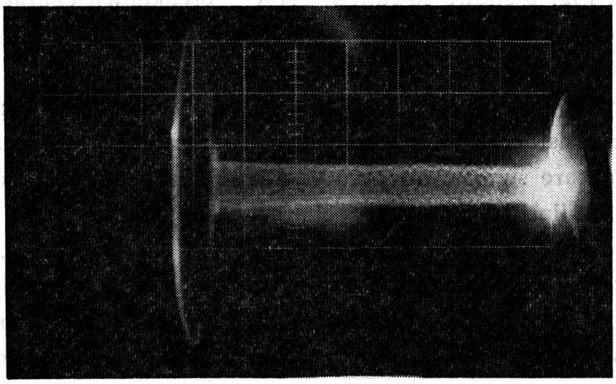

Fig. 6b. Multiplication characteristic of transistor shown in Fig. 6a.
H : 10 V/cm, Injection level 120 μA.

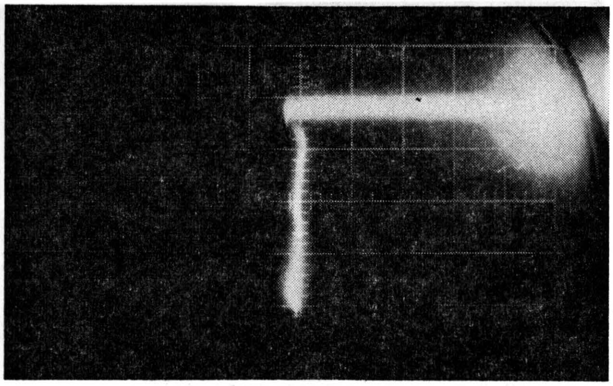

Fig. 7a. *V-I* characteristic of a transistor showing microplasma breakdown.
V : 1 mA/cm, H : 15 V/cm.

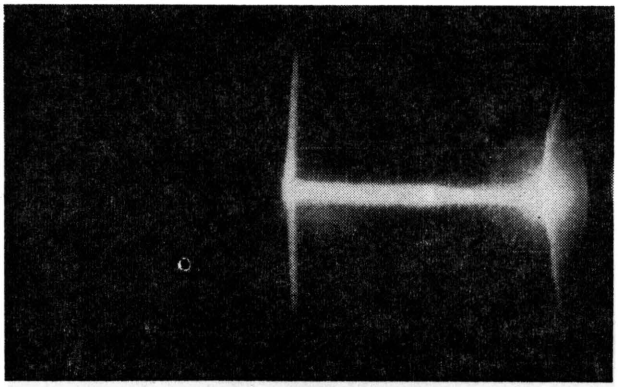

Fig. 7b. Multiplication characteristic of the transistor shown in Fig. 7a.
H : 15 V/cm, Injection level 80 μA.

The device of Fig. 5 shows so-called "soft" breakdown characteristics and its multiplcation increases in proportion to the collector voltage. This shows large leakage passes are existent in the periphery of the junction 3).

The transistors of Fig. 6 and Fig. 7 give "hard" breakdown characterisics with several negative resistances in the breakdown region and with small "jumps" of the current which are significant feature of microplasma breakdown 4). Although there are much similarities in the *V-I* characteristics between, the devices of Fig. 6 and Fig. 7, are quite different in the multiplication characteristics.

The multiplication characteristic of the transistor shown in Fig. 6 has nearly constant value of *M* as far as the breakdown region. Then *M* increases sharply and becomes its maximum at the breakdown voltage, while considerable amounts

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3) T. Suzuki and T. Sudo, IEE of Japan Convention, ♯1375, Apr., 1963.

4) B. Senitzky and J. L. Moll, Phys. Rev., 110, 612 (1958).

of M still remain beyond the breakdown voltage. On the other hand, the multiplication of the transistor in Fig. 7 shows smooth but steeper increase than the device in Fig. 5 as far as the voltage determined by the breakdown of a small localized spots, i. e. microplasmas[5]. At the breakdown voltage of microplasma, M increases very sharply and decreases beyond the voltage.

These results are taken with a triangular wave of 1 ms duration and of 50 ms interval and with 150 KHz for the frequency of the emitter driving signal. The ambient temperature is held at 78°K.

IV. Discussion and Conclusion

A number of transistors which show similar characteristics to those of Figs. 6 and 7 have often shown the dependence of M on amount of the injected current. This effect had been already reported by Batdorf, et al.[6] for silicon *p-n* junctions.

It is supposed that the difference of the multiplication characteristics between these two devices denotes the existence of two kinds of the negative resistances according to different defects in the junction. This new evidence on the avalanche effects will be reported in the near future.

In our measurement, the triangular waves of 1 ms～5 ms duration have been chosen, their intervals have been over 50 times of the duration.

The highest frequency for the emitter driving signal is limited by the equation

$$f < \frac{1}{2\pi R_c C_s}$$

where C_s is the stray capacitance including the collector junction capacitance and f is the frequency of the emitter driving signal.

C_s is about 100 pF in this apparatus. As the smallest value of R_c is 2 KΩ which has been determined by the S/N of the measuring apparatus, the frequency should be kept lower than 800 KHz.

The actual value for the duration should be determined with consideration of the frequency of the emitter driving signal, of internal heating and of the stray capacities in the measuring circuit. In the breakdown characteristics of the devices which show the hard breakdown and contain microplasmas, current is almost constant and small until the breakdown voltage, and increases rapidly, often discontinuously over the voltage. In the experiment, many devices have shown hard breakdown and their breakdown regions have been less than several volts. This means that the breakdown region cannot exceed 5 % of the whole applied voltage, when the peak collector current is held under 10 ma. This means also that the rise time of current wave-form becomes much faster than that of voltage wave-form. Hence the duration should be much larger than the time constant R_cC_s. 100 μs

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5) D. J. Rose, Phys. Rev., 105, 413 (1957).

6) R. L. Batdorf, et al, loc. cit.

duration has been barely possible while R_cC_s is about 200 ns when R_c is 2 KΩ.

In the measurement M, the duration is also limited by the frequency of the emitter driving signal while the duration of 100 μs is sufficient for the measurement of V-I characteristics, because it is necessary to increase a probability of the multiplication of the initial carrier in the breakdown region. As voltage is converted to time, in this method, the breakdown region means the period where breakdown occurs during one duration. Accordingly, the duration τ is the larger the more preferable in comparison with $1/f$ for an accurate measurement. Actually the ratio τ to $1/f$ has been decided by the experiment and the ratio over several hundreds has been found to be satisfactory. The duration should be less than the thermal time constant of the device because the maximum rise of the internal temperature can be determined by τ when a certain amount of power is applied to the device 7).

The results show good agreement with the multiplication charactreistics obtained by the photo-injection method. This method may be applicableto the investigation of defect structures in *p-n* junctions and of their effects on the breakdown characteristics. This method can be also applied to the calculation of an ionization coefficient of semiconductors when devices free from the defect structures are employed.

The measureing method is described in terms of germanium alloyed *pnp* transistors. However, this method is equally applicable to other active devices.

Acknowledgement

The authers are greatly indebted to Prof. M. Kobayashi for many helpful advices.

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7) T. Suzuki and H. Hirose, Proc. of Fujihara Memorial Faculty of Engineering, Keio University., 18, 69, p. 18 (1965).