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Current oscillation due to the interaction between the optical phonon and the electron stream

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A high efficiency sinusoidal abnormal current oscillation with the frequency of about 800 MHz has been observed in n-type bulk GaAs. The current wave form of the oscillation detected in the resistive transmission line was sinusoidal and the frequency did not depend upon the applied voltage. The large current modulation factor was observed. The current did not drop at the threshold of the oscillation but fluctuated around the mean value. Furthermore, the phase of the oscillation could be easily controlled adjusting the magnitude of the applied voltage in the stable region of the oscillation.

The threshold voltage of the oscillation increased heavily and the oscillation amplitude decreased with the ambient temperature. This oscillation is supposed to appear as the result of interaction between the optical phonon and electron stream.

1. Introduction

In 1965–1966, Shuskus and Shaw reported an "abnormal oscillation" observed in n-type GaAs for which the characteristics were different from Gunn mode oscillation[1,2]. However they interpreted it using the two valley mechanism[2,3]. In the course of our studies of the Gunn oscillation, a clean sinusoidal oscillation has been detected from bulk GaAs. This oscillation has several characteristics that differ from the usual Gunn oscillation and the limited space charge accumulation mode (LSA) oscillation. In some ways, our observed oscillation is different

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1) A. J. Shuskus and M. P. Shaw: Proc. IEEE 53 (1965) 1804.
2) M. P. Shaw and A. J. Shuskus: Proc. IEEE 54 (1966).
3) M. P. Shaw, P. R. Solomon and H. L. Grubin: Appl. Phys. Lett. 17 (1970) 535.

from Shuskus and Shaw's oscillation although in many ways they are similar. From the experiment, this oscillation was found to be not due to the relaxation oscillation, the LSA oscillation. Instead, it is supposed that this oscillation is due to the optical phonon and electron stream interaction[4, 5].

2. Sample Preparation and Measuring Circuit

The crystals used in this experiment were fabricated by Monsanto Co. The crystal orientation was (111), and the electron concentration and the mobility were 1.0 x 10^{15} cm^{-3} and 5,160 cm^2 V^{-1} sec^{-1}, respectively. Wafers of about 1.4 x 1.4 mm^2 in area were etched in sulphurric peroxide etchant and washed in deionize water. The ohmic contact were formed by alloying in dots on both sides of the wafer. The thickness of the wafer was about 0.2 mm. In Fig. 1, a photograph of the typical sample fabricated is shown.

Fig. 1. Photograph of a diode.

The diodes were measured in a resistive transmission line and a cylindrical cavity. Fig. 2 (a) and Fig. 2 (b) represent the equivalent circuit. In Fig. 2 (a), the current through the sample was evaluated using the voltage appeared across the small resistance R_2 and the voltage across the sample was obtained measuring the voltage across the resistance R_1 which is approximately equal to that across the sample. Fig. 2 (b) indicates the equivalent circuit of the cylindrical cavity whose center frequency is 150 MHz. The resonant frequency of the cavity is adjusted by the change of the cavity length. In this case, the sample is fixed in to the special package and mounted in to the resistive transmission line near the cavity connected to it as shown in the figure. The current voltage characteristics and current and voltage wave form

4) J. B. Gunn: Phys. Lett. 4 (1963) 194.
5) M. Sumi: IEEE Trans. Electron Devices 13 (1966) 53.

were measured on a sampling oscilloscope by applying a pulse voltage of 100 nsec at a repetition rate of 50 sec^{-1}.

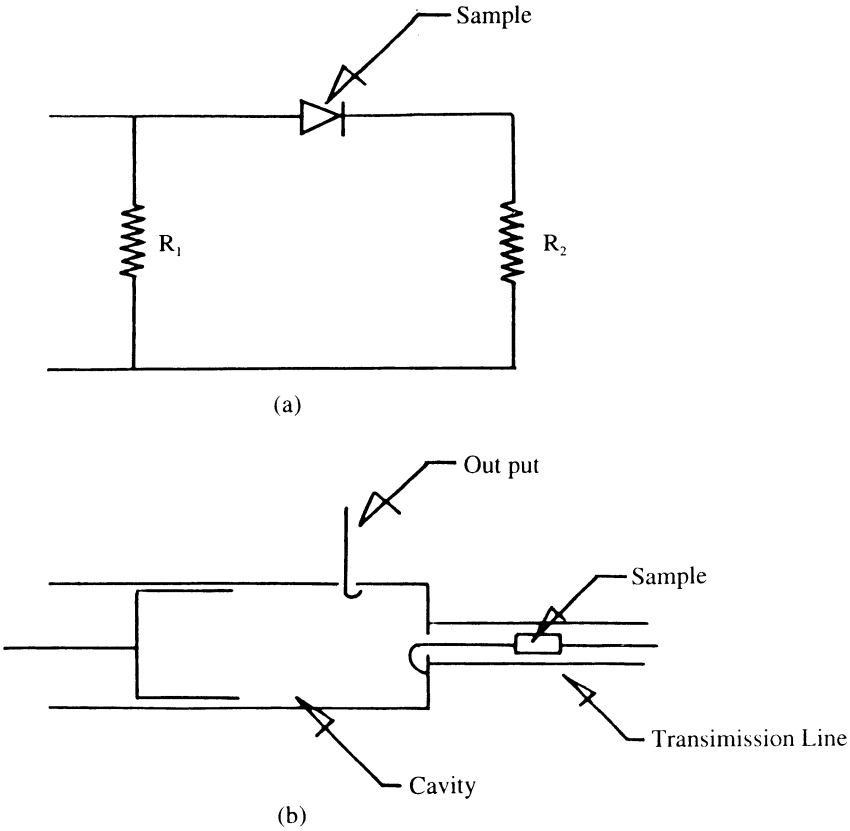

Fig. 2. Measuring circuit.

3. Experimental results

3. 1 Current voltage characteristics and oscillation wave form

Fig. 3 represents a typical example of the current voltage characteristics for good diode measured by the resistive transmission line. As can be seen in the figure, in the low voltage region the current increased almost linearly and then saturated very gradually. The current fluctuation appeared at a field strength of about 2,500 V cm^{-1} in this diode. This fluctuation was not enlarged until the field strength was increased to about 5,000 V cm^{-1}. The fluctuation is thought to be due to the uncomplete Gunn effect. A sinusoidal current oscillation appeared at the field strength of 6.050 V cm^{-1}. It should be noted here that the current did not drop at the threshold bias as the case for a clean Gunn oscillation but instead oscillated around the mean value of the current. This resemble the oscillation observed in piezoelectric semiconductors[6]. The oscillation amplitude increased gradually with the applied voltage over a broad region and finally saturated.

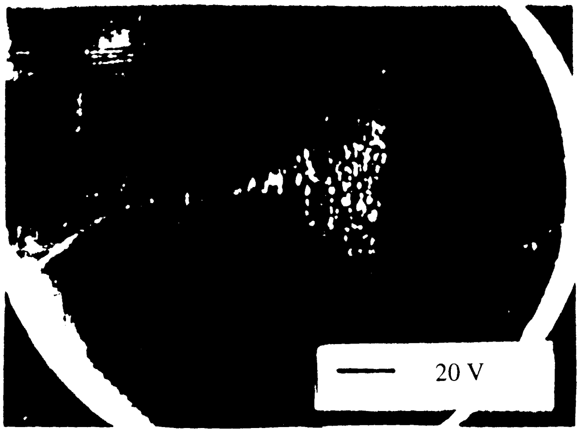

Fig. 3.　Current voltage characteristic of a typical diode

Fig. 4 shows the typical waveforms of a current oscillation (bottom) and a voltage oscillation (top). The current waveform was sinusoidal every time even when the diode was mounted in a resistive transmission line. This is different from the behavior of the Gunn diode.

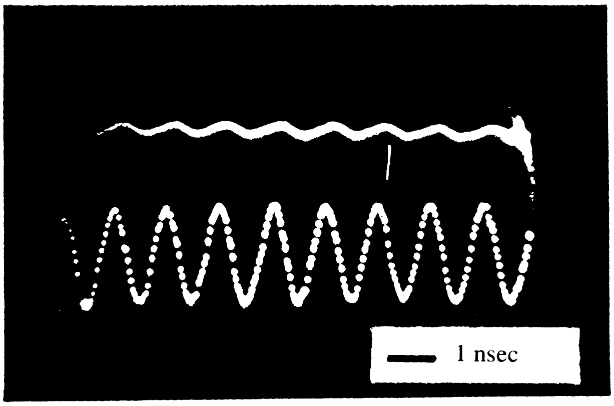

Fig. 4.　Current and voltage waveforms of a typical diode

3. 2　Voltage dependence of current oscillation

In this subsection, the voltage dependence of oscillation waveforms appeared at various voltage is shown. Fig. 5 shows the voltage dependence of the sinusoidal oscillation observed

6）R. W. Smith: Phys. Rev. Lett. 9 (1962) 87.

in a typical sample whose current voltage characteristic is shown in Fig.3. Fig.5 (a) shows the current and voltage waveforms as a function of time below the threshold. Any current fluctuation can not be seen at this voltage. At a lower voltage, the current fluctuation as shown in Fig. (b) appeared. The current fluctuation in this case is very small and not coherent. This is thought to be the uncomplete Gunn oscillation. This small current fluctuation changed into the sinusoidal current oscillation as shown in Fig. 5 (c) at the voltage of 121 V. The coherency of the current oscillation in this case is not complete yet. Further increase of the applied voltage brought the very coherent sinusoidal oscillation. The amplitude of current oscillation was not increased

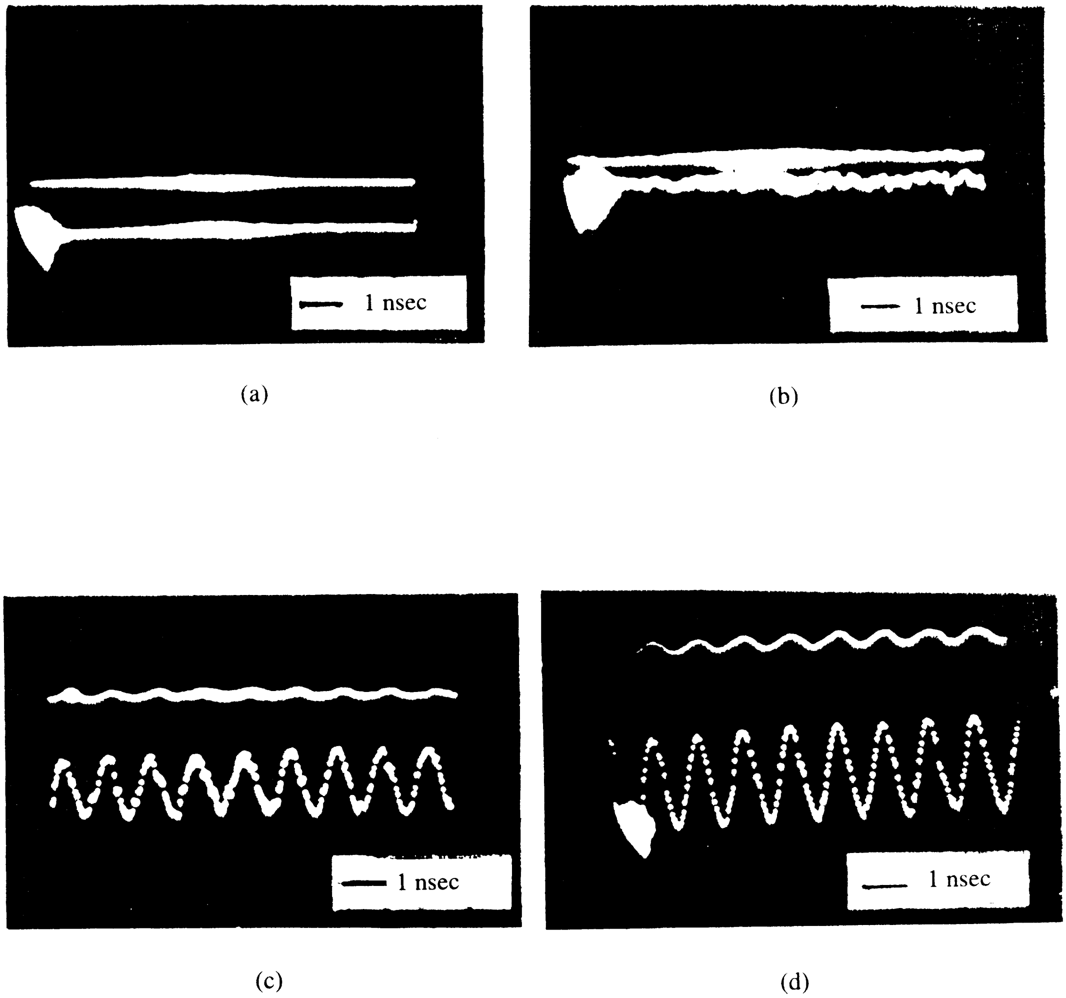

Fig. 5. Voltage dependence of current oscillation.

further. That is, it saturated at the voltage of 134 V in this sample as shown in Fig. 5 (d). Almost all samples fabricated suitably gave similar characteristics. In the Gunn oscillation, the current spike appears suddenly at the threshold and the spike is not enlarged when the applied voltage is increased. As can be found in the figure, the oscillation frequency did not change even when the applied voltage is adjusted in the fairly broad region.

3. 3　Current modulation factor

As was pointed out previously, the current did not drop at the threshold but fluctuated around the mean value as indicated schematically in Fig. 6. The modulation factor, defined as $IMF=2I_A/I_M$, was very large compared with the Gunn oscillation and ranged from 0.4 to 0.8. The beginning of the current oscillation is shown in Fig. 7.

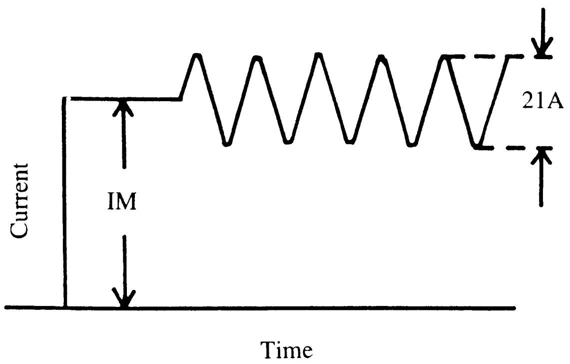

Fig. 6.　Definition of the current modulation factor.

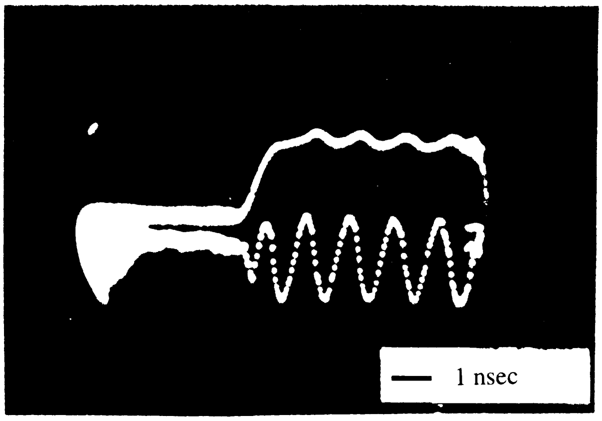

Fig. 7.　Beginning of the current oscillation.

3. 4　Controlling of the phase of the current oscillation

The phase of the current oscillation changed rapidly after sudden change in the applied voltage in the stable region of the oscillation. An example is shown in Fig. 8. The voltage was changed at the point denoted by the arrow. This effect was not seen in the Gunn diode even when a similar process was made.

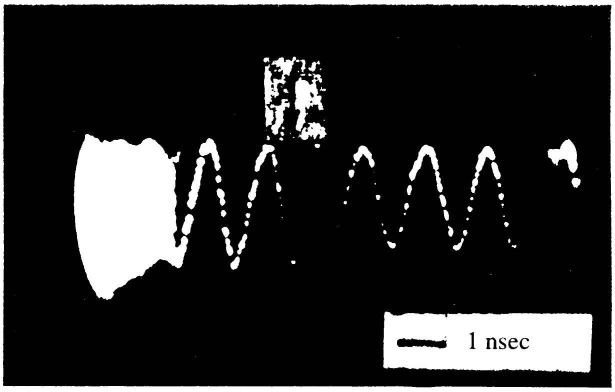

Fig. 8. Controlling of the current oscillation phase by adjusting the applied voltage.

3. 5 Characteristic of the current oscillation in the resonant cavity

The oscillation waveform was observed by mounting a diode into the cavity. A typical wave form is shown in Fig. 9. As is seen, the high frequency oscillation shown in Fig. 5 is modulated by the low frequency wave whose frequency corresponds to the resonant cavity frequency. It is significant that the frequency of the high frequency oscillation is not adjusted by the change of frequency of the cavity. This is very different from the behavior of the LSA oscillation. The fact that the lower frequency oscillation, whose frequency is the resonant frequency of the cavity, appears shows the presence of the negative resistance. The presence of the negative resistance for this oscillation is explained by Sumi[5]. This behavior has not be

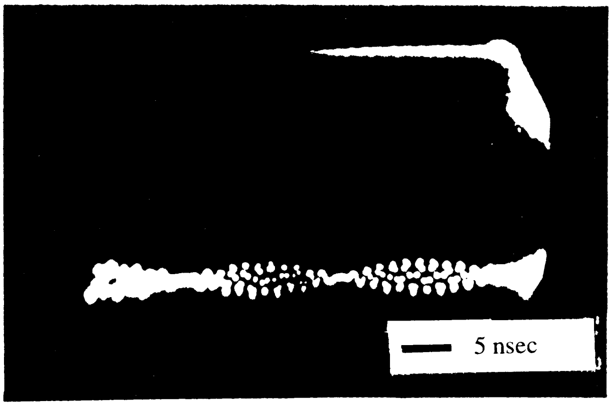

Fig. 9. Current oscillation in a cavity.

5) M. Sumi: IEEE Trans. Electron Devices 13 (1966) 53.

seen in the Gunn oscillation.

Shuskus' oscillation was tunable with voltage. The frequency of this oscillation was independent on the applied voltage over a broad voltage range.

3. 6 Effect of ambient temperature on oscillation characteristics

This current oscillation was sensitive to the ambient temperature. The threshold field increased heavily and the oscillation amplitude decreased with increasing temperature. The current voltage characteristics of a diode at different ambient temperature are shown in Fig. 10. In the figure, it is seen that the threshold voltage of this oscillation is heavily enlarged although the threshold of uncomplete Gunn oscillation is similar with each other. It is known that the threshold voltage of the Gunn oscillation is not sensitive to the temperature or decreases with the temperature. This characteristic indicates strongly that this oscillation is not Gunn oscillation.

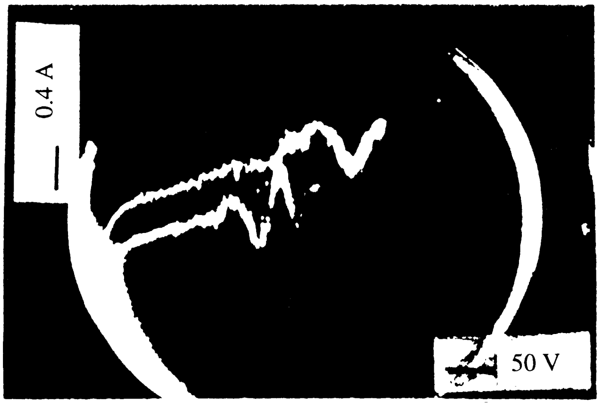

Fig. 10. Effect of ambient temperature on current voltage characteristic.

4. Discussion

From the several experiment mentioned above, it can be concluded that this oscillation is not the Gunn oscillation or the LSA oscillation. This oscillation resembles that observed in piezoelectric semiconductors by Smith[6]. However, the frequency of this oscillation is higher by a few order of magnitude. The author believes that this oscillation is due to an interaction between the optical phonon and a stream of electrons[4, 5, 7]. In many cases, this oscillation is

6) R. W. Smith: Phys. Rev. Lett. 9 (1962) 87.

7) T. Hayashi, A. Hasegawa and R. B. Uehlein: Trans. Ins. Electron Comummn. Eng. Jpn. J69C (1986) 162 (in Japanese).

supposed to appears after the Gunn oscillation[2], or arises in lower electron density samples than that of Gunn diodes. From Sumi, the frequency of the oscillation is given by (V_0/L)[5]. Where, V_0 is the electron velocity, L the diode length and N a positive integer. In the case of oscillation shown in Fig. 5 (d), the field in the diode was 6,700 V cm^{-1}. We can estimate the value of electron velocity at this field from Ref. 8 as 1.5 x 10^7 cm sec^{-1}. When we use this value, the frequency of the fundamental mode becomes 700 MHz. This coincides approximately with the frequency of Fig. 5 (d).

The higher value for the threshold field of this oscillation than for the Gunn oscillation has been pointed out by Sumi, also[5]. The random vibration due to phonon is expected to become viorent with an increase of ambient temperature. This can explain in the thermal effect on this oscillation described above. Next, as a result of the fact that the new wave may be built up corresponding to a certain voltage, we expect the observed phase controlling phenomena. In the case of the Gunn diode, an increment of the applied voltage may be absorbed in the high field domain and no wave is excited. In this case, it is understandable that the oscillation frequency does not depend on the applied voltage because the electron velocity at the very high electric region is not sensitive to the field[8]. Finally the fact the oscillation does not drop at the threshold and the current waveform is sinusoidal are understandable from the model we described. We expect this phenomenon will be useful as a high efficiency microwave source.

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8） S. M. Sze: Physics of semiconductor Devices (Wiley, New York, 1969) 59.