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Excess Noise in Narrow Germanium *p-n* Junctions

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Excess noise has been studied on narrow alloyed *p-n* junctions fabricated on heavily doped *p*-type and *n*-type germanium with less than 200 Å junction width, which exhibit inverted rectification and negative resistance in the forward direction. Considerable $1/f$ noise has been observed in a forward range, the character of which is stable and surface insensitive. Moreover, the noise was found to be mainly associated with the excess forward current that is peculiar to narrow *p-n* junctions. Measurements were made also at low temperatures down to 77°k on both noise and static characteristics. The origins of the excess forward current and the associated excess noise were discussed in connection with the crystal imperfection.

§ 1. Introduction

In the recent experiment by one of the authors,[1),2)] it was found that extremely narrow *p-n* junctions fabricated on heavily doped degenerate germanium exhibit much different current-voltage characteristics from those of the usual *p-n* junctions. The main features encountered are the inversion of rectification direction** and the existence of negative resistance in the forward direction. Both features are fairly well explained by considering Zener current, or internal field emission, across the energy gap at the junction. Moreover, various new effects will be expected associated with the properties of the material having high impurity concentrations. Therefore, the noise properties have been studied here as an inherent character of the device.

It has been well known that $1/f$ noise, or excess noise, appears commonly in almost all semiconductor devices and crystals accompanied with flowing current while it is absent in metals. In semiconductor crystals, however, an experimental tendency that the magnitude of $1/f$ noise becomes lower with the decrease in resistivity might be probably accepted. Actually, it is usually difficult to observe $1/f$ noise in germanium single crystal filaments with the resistivity below about 1 ohm-cm. On the one hand, $1/f$ noise is belived to be predominantly a surface effect, because of its large dependence on surface conditions especially for reverse biased usual diode. Accordingly, most of the existing $1/f$ noise theories[3)] include the surface as a part of the model, though exact picture has not yet been established.

Considering above facts, it was simply expected at first that the narrow *p-n* junction will have very low or no detectable $1/f$ noise, since the device is composed of metal-like semiconductor with extremely low resistivity of the order of 10^{-3} ohm-cm and its static characteristics are quite stable to surface conditions in the whole bias range. Practically we observed considerable $1/f$ noise in a certain bias range, and its properties were found to be somewhat different from those of the usuall *p-n* junctions in several points. This is a subject of interest as a particular example of $1/f$ noise. It is the purpose of the present paper to describe the experimental results about this $1/f$ noise and to discuss the underlying physical processes.

§ 2. Samples and Noise Measurement

The samples are fabricated by alloying technique on heavily doped *p*-type and *n*-type

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** In this paper, we defined the *forward* direction of any *p-n* junction as the case where *p*-side is positively biased relative to *n*-side, regardless of the relative easiness of the current flow.

Table I.

Sample	Base Crystal				Alloying Dot
	conductivity type	doping agent	impurity content (cm^{-3})	resistivity (ohm-cm)	component
5-12	p	pure Ga	1.6×10^{19}	0.0021	0.5–1% P–In
IID-3	n	intermetallic In–P	1.2×10^{19}	0.0015	0.5% Ga–In

germanium of $10^{18}\sim3\times10^{19}$ cm^{-3} impurity concentration. The main features of the typical units used are listed in Table I.

Fig. 1 shows typical current-voltage characteristics of the narrow p-n junction. Large current in the reverse direction and current peak in the low voltage forward region can be attributed predominantly to Zener current corresponding to the electron transition between valence band and conduction band at the junction.[1),2)] The current peak appears for the units having above about 2×10^{18} cm^{-3} impurity concentration, and the higher the concentration the higher the height of the peak. In the large forward voltage range, the observed characteristics were found to obey the usual diode current voltage relation

$$I=I_s[\exp(qV/kT)-1]$$

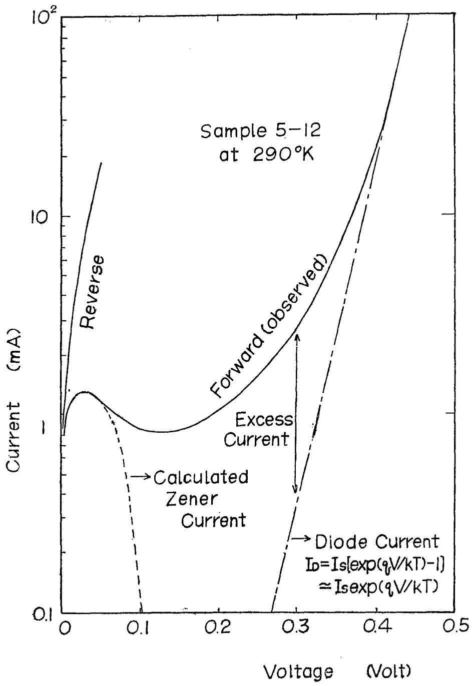

Fig. 1. Current—voltage characteristics of narrow p-n junction.

where q is the electronic charge, k is Boltzmann constant, T is the absolute temperature, and I_s is a constant. The whole static characteristics are quite stable both for ambient variation and light illumination unlike usual p-n junctions.

There still remains, however, an excess current component dominantly observable in the range from 0.2 volt to 0.4 volt at room temperature. Though the nature of this current component has not yet been completely explained, it was found to be related closely with the observed excess noise. This is the principal subject of this paper, and the more details will be described in the later sections.

Noise measurements were performed in the usual manner according to the circuit diagram as shown in Fig. 2. For the sample with large nonlinearity as in this case, it is necessary to determine the mean square short-circuit noise current $\overline{i_{ns}^2}$ and/or the mean square open-circuit noise voltage $\overline{v_{no}^2}$ correctly in order to know the intrinsic noise behavior of the units, because load resistance affects the observed noise characteristics considerably. ($\overline{i_{ns}^2}$ and $\overline{v_{no}^2}$ are simply related as $\overline{v_{no}^2}=r^2\,\overline{i_{ns}^2}$, where r is the dynamic resistance of the sample). In the present case, they are determined through the simple circuit relations, using the measured values of the output noise voltage across a given load resistance and the sample dynamic resistance. Actual measurements were made approximately

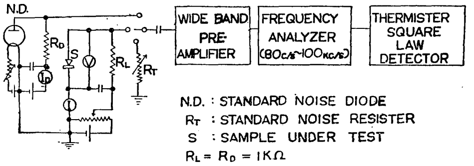

Fig. 2. Circuit diagram of noise measuring sistem.

under the open-circuit conditions due to the low sample resistance.

§ 3. Experimental Results

In the whole reverse region and in the forward region up to the current peak, we observed no detectable excess noise even for the open-circuit conditions. The situatisn is the same for negative resistance range. In this range, however, we were obliged to use very low load resistance below 10 ohm to set a stable bias, which results in great undesirable decrease of sensitivity of noise measurement. Although these results might be partly due to the low dynamic resistance of the sample, it seems to show that Zener current dominant in these range does not accompany particular excess noise. This seems to be in accordance with the previous results by other workers for less narrow *p-n* junctions.[4]

On the other hand, considerably excess noise was observed beyond the current minimum in the forward direction. The frequency spectrum was found to show typical $1/f$ character and to be much higher above thermal and shot noise with white spectrum as indicated in Fig. 3. Also, this noise is fairly stable without pulsive character, and relatively surface insensitive. Even for the heavy ambient conditions, that is, dipping in water and some organic liquids such as benzene, carbontetrachloride, ethylalcohol, or, for the re-etching of the samples, no appreciable changes of both noise and static characteristics were found. This is in contrast with the behavior usually associated with the $1/f$ noise.

The variation of the noise with the forward

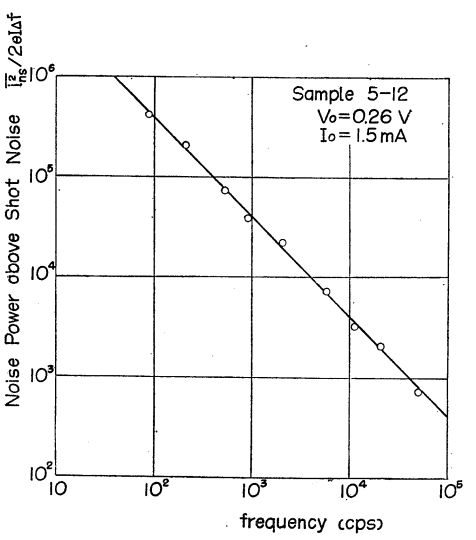

Fig. 3. Noise frequency spectrum of narrow *p–n* junction.

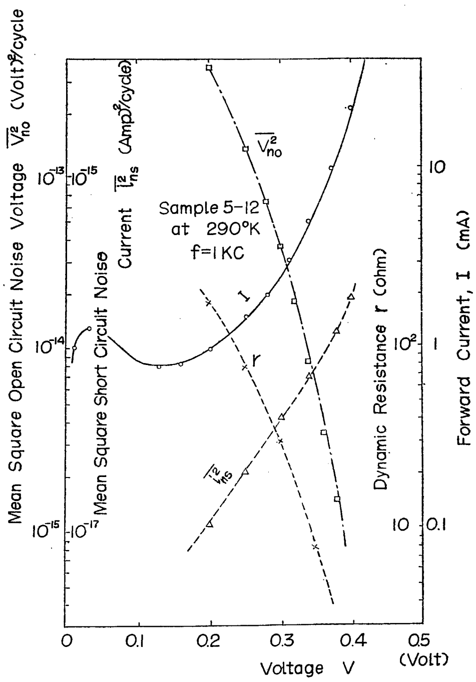

Fig. 4. Noise and current-voltage characteristics of narrow *p–n* junction.

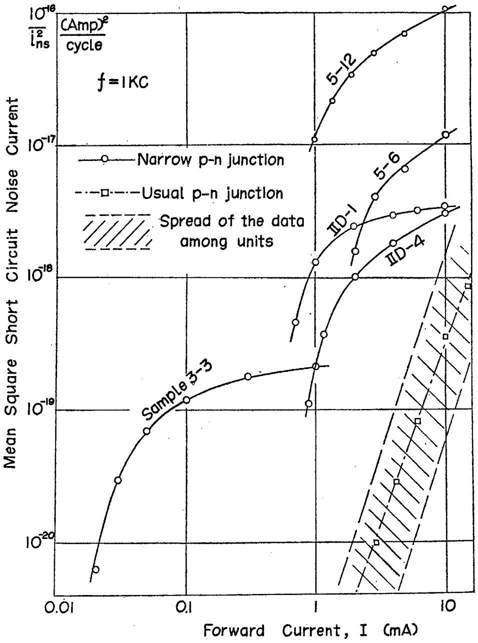

Fig. 5. Mean square noise current as a function of forward current for narrow and usual *p–n* junctions.

voltage is shown in Fig. 4. The outstanding feature is that the mean square open circuit noise voltage $\overline{v_{no}^2}$ decreases rapidly with the bias voltage, while mean square short circuit noise current $\overline{i_{ns}^2}$ increases. From a simple equivalent circuit consideration, this can be interpreted as that the noise source is concentrated at the junction as a form of current generator which is nearly identical with i_{ns}, and that the decrease in $\overline{v_{no}^2}$ with the bias voltage is due to the change of barrier resistance of the junction. It is noted, however, that no such decrease in $\overline{v_{no}^2}$ has been found in the forward range of usual *p-n* junctions. Series or bulk resistance seems to contribute to the excess noise in direct or indirect way in the latter case. In Fig. 5, $\overline{i_{ns}^2}$ of several units are plotted as a function of the forward current, simultaneously compared with that of the usual forward biased alloyed *p-n* junctions. The latter represents an average characteristics of the excess noise of randomly selected 20 units, and the spread of the data among units is indicated by the hatched section. Two points should be noticed about the difference between narrow junctions and usual junctions. First, the noise level of narrow junction is much higher than that of the usual junction in the forward direction. Second, the current dependence of the noise for narrow *p-n* junction deviate greatly from the normal square-law relation, i.e., $\overline{i_{ns}^2} \propto I^2$, for the $1/f$ noise, while it is nearly normal for usual junctions.

Above results can be interpreted phenomenologically in the following way. In the case of usual germanium *p-n* junction diode, the observed forward current is known to consist almost only of the theoretical diode current, though modified by the series resistance, and hence the fact of normal current dependence for the excess noise may naturally be accepted. On the other hand, the forward current of narrow junction consists of three components, i.e., Zener current, diode current, and excess current, as described previously. In the voltage region of interest, the contribution of the theoretical Zener current will be negligible, and hence the last two components are sufficient to be considered. Since these two components can be thought to have different origins, it will be natural to consider different $1/f$ noise sources for each component. Then, the spectral density of the observed noise current may be the sum of two independent mean square noise current generators accompanied by the diode current and the excess current, respectively, and is expressed by

$$\overline{i_{ns}^2} = K_1 \frac{I_d^2}{f} + K_2 \frac{I_{ex}^2}{f}$$

where I_d is the diode current, I_{ex} is the excess current and K_1, K_2 are the proportionality constants of different values. It is easily shown that in this case $\overline{i_{ns}^2}$ cannot be proportional to the square of the total current, $(I_d + I_{ex})^2$, unless I_d is always proportional to I_{ex}. This might explain the departure from the square-law current dependence. Furthermore, suppose that the excess current is much noisier than the diode current, i.e., $K_1 \ll K_2$, as is guessed from the results in Fig. 5. Then, the square-law relation between the noise and the excess current, instead of the total current, will be expected. By the method indicated in Fig. 1, we can always obtain the excess current as a monotonic increasing function of the voltage, except in the small region where normal diode current dominate extremely over the excess current and so the estimation of the latter becomes uncertain. Thus

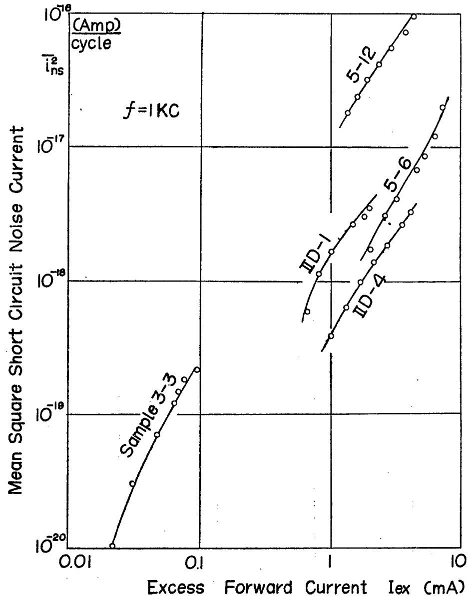

Fig. 6. Mean square noise current as a function of excess forward current for narrow p–n junctions.

we can plot the noise as a function of the excess current as shown in Fig. 6. The results yield the relation fairly close to square-law for most of the measured samples as expected. This seems to be a strong indication that the excess noise in narrow *p-n* junction is mainly accompanied with the excess forward current. This is quite analogous to the situation that the excess noise in usual reverse-biased *p-n* junction arises mainly from the leakage or excess reverse current,[5] although physical origins of these two excess currents might be quite different.

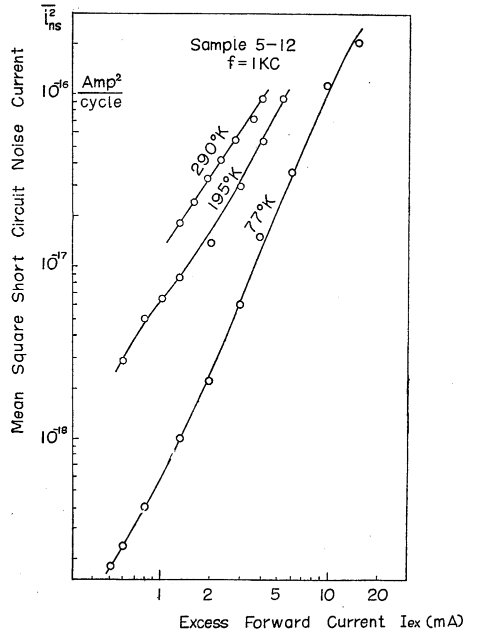

Fig. 8. Mean square noise current as a function of excess forward current for narrow *p–n* junction at low temperature.

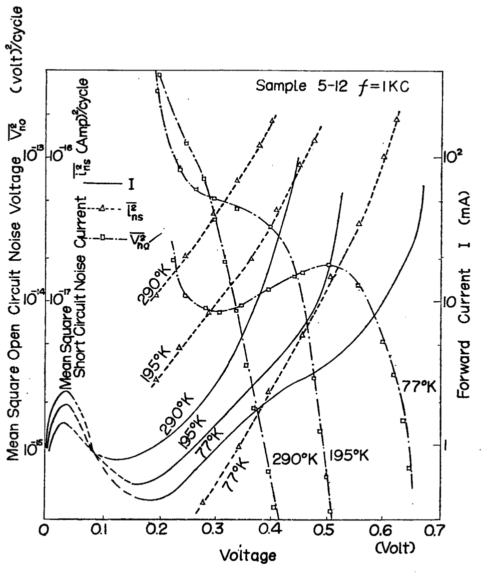

Fig. 7. Noise and current-voltage characteristics for narrow *p–n* junction at low temperature.

To understand the phenomena more clearly, measurements were made at lower temperatures of 195°k and 77°k. The results are shown in Fig. 7 and Fig. 8. Following features were found concerning to the excess current;

(1) The excess current is relatively independent on temperature both in its magnitude and voltage dependence, and hence it becomes dominant at low temperature because of the rapid decrease of the diode current.

(2) The excess current varies nearly exponentially with voltage.

(3) The excess current vs. voltage curve has a gradual hump which appears more clearly for lower temperatures, but still keeping to be a monotonic increasing function.

Similarly, the results of noise measurements are summarized as follows;

(1) At low temperatures $\overline{v_{no}^2}$ varies in a complicated manner with the forward voltage, while $\overline{i_{ns}^2}$ increases monotonically. This again seems to indicate that $\overline{i_{ns}^2}$ represents more direct physical nature of the excess noise.

(2) $\overline{i_{ns}^2}$ shows nearly normal current dependence as a function of the excess current even at low temperatures, which might be a further support for the relation between the excess noise and the excess current.

(3) The magnitude of the noise always decreases with decreasing temperature but not so strongly. This is in contrast with the situation that in the usual *p-n* junction transistors, the excess noise associated with the emitter current shows considerable increase at low temperatures.[6]

§ 4. Discussion of the Results

Summarizing all the results mentioned above, it may be believed that the observed $1/f$ noise is a pure junction effect associated with the remarkable excess forward current, and the understanding of the latter will afford a key to the understanding of the former.

Since we have not yet get a satisfactory explanation, only a brief qualitative discussion will be given below. The nature of the excess forward noise in usual *p-n* junction, which is the problem to be solved at the sametime, will not be concerned here.

First, it might be quite natural to suppose that the excess current is caused by some kinds of crystal imperfections, such as the dislocations or the impurity aggregate, due to the heavy doping. In fact, etch pit observation showed many characteristic pit clusters when the impurity amount becomes as high as $10^{20}\,\mathrm{cm}^{-3}$. However, the possibility of any current mechanism, arised from the thermal process governed by the activation energy or the potential barrier, may be excluded because of the relatively weak temperature dependence of the excess current. The current through local ohmic contacts is a possible cause with the desired temperature dependence. But it may be improbable because observed characteristics are non-ohmic, and noisy ohmic contact is unlikely. Another possibility is some non-ohmic leakage current through the imperfection at the junction, which can be large because of the small effective leakage path length due to narrow junction width. Surface leakage will also come to mind from the analogy of usual junction, but this must not be predominant, if present, since any heavy surface conditions do not greatly affect the characteristics as described previously. Now, one might question whether the excess current is peculiar to narrow *p-n* junctions or not. According to our measurements, we could not find such distinct excess current in the usual forward biased *p-n* junctions even at the liquid nitrogen temperature. This result seems to suggest that the excess forward current is governed not only by the degree of imperfection, even if it were so, but also by some another properties directly associated with the narrow junction width.

At this stage, an idea of another type of internal field emission will be proposed as a cause of the excess current. This can be considered to be present *in addition to* the internal field emission, previously introduced to explain the negative resistance, by the following reason. Since the internal field emission of the type described previously is the one produced by the direct interband electronic transition at the junction, it must go to zero above the critical forward voltage where the bottom of the conduction band in the *n*-side coincide with the top of the valence band in the *p*-side.$^{1),2)}$ This voltage is derived from the position of the Fermi level, and is estimated theoretically as ranging about 0.1~0.2 volt depending on the impurity concentration and temperature. Then, if any internal field emission mechanism is to be considered above this value, it must occur through the additional energy levels in the forbidden gap. Since there are many experimental evidences for the existence of such levels associated with the impurities and the dislocations, it will not be impossible that this new type of internal field emission causes the excess forward current with the temperature-insensitive character. Although we will not proceed further because of the lack of the necessary knowledge to treat the problem quantitatively, one following fact might be worth noticing. Namely, as is shown in Fig. 7, the excess current has a gradual but clear hump at low temperature centered in the range about 0.3~0.4 volt corresponding to about the half of the energy gap, and sometimes noise current also showed similar hump in the corresponding range. Since some impurity or dislocation levels are known to lie near the midgap in germanium, this would seem to suggest a correlation between these levels and the excess current.

If this is true, the associated excess noise will be understood naturally according to the following modulation mechanism. Appart from the explicit details, it is evident that the current produced by this cause will strongly depend on the situation of the imperfections and the associated field distributions near the junction. Since there would be the statistical fluctuations of the trapping and recombination processes through these levels such as suggested by Morrison$^{7)}$ or of the impurity state itself, the resultant fluctuation of the population or the number of levels and of the neighbouring field distributions will strongly modulate the field emission current associated these levels. Further, if these modulation sources have $1/f$ type fluctuation, $1/f$ noise must arise.

Of course, above explanation is only a possibility, and it is hoped to seek more reasonable point of view in future. There will be also a question whether the $1/f$ noise described here is actually different from the usual surface-sensitive $1/f$ noise in its intrinsic nature. Regarded from the general appearance of $1/f$ noise, it seems to be desirable to consider unified model for all the units exhibiting $1/f$ noise. However, it may be possible or even natual to suppose that the different physical causes of $1/f$ noise dominate for different types of device, as far as the underlying statistical elementary processes satisfy the mathematical requirement for the derivation of $1/f$ type spectrum.

In conclusion the authors wish to express their thanks to Miss Y. Kurose for her assistance in the experiment and the calculations.

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