ON THE BEHAVIOUR OF SEMICONDUCTOR RECTIFIERS AT HIGH CURRENT DENSITIES

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1. Introduction

We are, as to the theories of semiconductor rectifiers, interested in the study of the behaviour of rectifiers to the current-voltage relations at high current densities, because we have a hope to know the ionization mechanism of electrons in the semiconductors. We can make clear what theory is adequate to the semiconductor rectifiers by measurement of the current-voltage curves depending on temperature.

If the electrons are excited by phonons from the impurity centres in the semiconductors of the rectifiers, we will observe the temperature dependence of the current-voltage relations at sufficiently high inverse voltage.[a] If, on the contrary, the electrons are excited by the direct ionization with strong electric fields,[b] we will not observe any temperature dependence, The pulsatory measurements at high current densities tell us clearly what mechanismus of excitation is the case for the semiconductor rectifiers.

The author measured the current-voltage relations of various kinds of semiconductor rectifiers with single pulsatory waves at high inverse current densities. The apparatus used in the measurements is the same as in the previous paper.[c]

It is needed for the experiment to use pulsatory waves, especially single pulsatory waves as distinct from the ordinally repeated pulsatory waves, because otherwise the temperature of the rectifiers rises unfavourably. The highest current measured with the cat-whisker type rectifiers is about 1 ampere, and the highest current densities measured with the plate rectifiers is about 10 amperes per square centimeter.

The conclusions we got are the following; adiabatic negative resisitances are observed in the germanium rectifiers; more larger negative resistances are observed in high-inverse selenium rectifiers and cuprous oxide rectifiers at high temperature; the temperature dependences of the current-voltage relations get smaller as the current densities get larger in selenium and cuprous oxide rectifiers; we can get a consistent explanation which holds not only to the present experiment but also to the measurements of high frequency impedance and the creep phenomena of the rectifiers.

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[a] cf. for example, Ono M. **1952** Memoirs of the Faculty of Engineering, Nagoya University, 4, 57.

[b] Zener C. **1940** Proc. Roy. Soc. (A), 145, 532 (1934); Houston W. V. **1940** Phys. Rev., 57, 184.

[c] Ono M. **1952** Memoirs of the Faculty of Engineering, Nagoya University, 4, 63.

2. Current-voltage relations of the rectifiers

According to the generalized theory by Landsberg,[d] the current (j)-voltage (U) relations are given by,

$$j=j_0 y^{3/2} \exp(y)$$

in the case of the diffusion theory, or

$$j=j_0 \exp(y)$$

in the case of the diode theory. There $y=[(V_D-U)/V_0]^{1/2}$, $V_0=\varepsilon dk^2T^2/e^2$ for the Mott barrier, and $y=[(V_D-U)/V_0]^{1/4}$, $V_0=\varepsilon^3k^4T^4/(8\pi ne^6)$ for the Schottky barrier.

The current-voltage relations depend on temperature as we can easily see from the above equations. In accordance with the above theory, temperature dependences are found also at high bias voltages. But the experimental fact at high current densities as described in this paper differs from the above theory. The current-voltage relations are independent of temperature at high inverse current densities. This fact tells us that the image forces are not the main mechanism to explain the high inverse current and voltage relations.

At sufficiently high inverse voltages of the rectifiers, constant resistances are got from the Mott's theory, if the image forces are not taken into account. The resistances at sufficiently high inverse voltages are expressed in $R_\infty=evn_1/d$, where v is the mobility of an electron, n_1 is the density of the electron and d is the thickness of the blocking layer. We can got the same expression to the values of the resistances without the theory of rectification. That is, the expression is the same as to the resistance of the blocking layer as a dielectric, having the thickness d, the mobility v and the density of electrons n_1 in the conduction band.

The well known two theories explain the decrease of the resistances of the rectifiers when the inverse bias voltages get larger. The one is the thermal ionization theory; the potential barrier of an electron decreases with the increase of the electric fields, in other words the conductivity increases as results of the decrease of the ionization energy. In this case, the conductivity increases as $\exp(\alpha E^{1/2}/kT)$ with the intensity of the field E. Image forces in the theories of rectification are just the case. For example, the resistances at inverse voltages are given by Mott[e] as $R=R_\infty \exp[-e^{3/2}E^{1/2}/(\kappa\, dkT)]$. It is remarkable that in this case the resistances of the rectifiers are strongly dependent on temperature, and the temperature dependencies get larger as the field intensity E increases.

The other is the electrostatic ionization theory.[b] The number of electrons in the conduction band increases with direct separation of electrons from the atoms under intense electric fields. In this case, the conductance increases with the field E as $\exp(-\beta/E)$. The resistances of the rectifiers at high inverse voltages are independent of temperatures.

We can determine which theory is the case for the semiconductor rectifiers by measurement of the resistances at high inverse voltages depending on temperature.

3. Germanium rectifiers

It is well known that there are negative resistances in the germanium rectifiers

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[d] Landsberg P. T. **1951** Proc. Roy. Soc. (A), 206, 463.

[e] Mott N. F. **1939** Proc. Roy. Soc. (A), 171, 27.

at sufficiently high inverse voltages. The negative resistances are explained by Benzer[f] and Hunter[g] to be the adiabatic self-heating effect.

If the explanation is the case, we need not get any negative resistance by the pulsatory waves, for we can measure the current-voltage relations without any heating. Bennett and Hunter[h] measured a germanium rectifier with the repeated pulsatory waves of 0.5 microsecond breadth, and they could not find negative resistances up to the inverse current of about 20 miliamperes, where the static curve shows negative resistances.

The author measured the germanium rectifiers with the single pulsatory waves of various widths. The highest current measured in the experiment is about 1,000 miliamperes. We could see that the negative resistances are found in the germanium rectifiers at higher current densities than was measured by Hunter.

Fig. 1 and Fig. 2 are the current-voltage relations got in the germanium

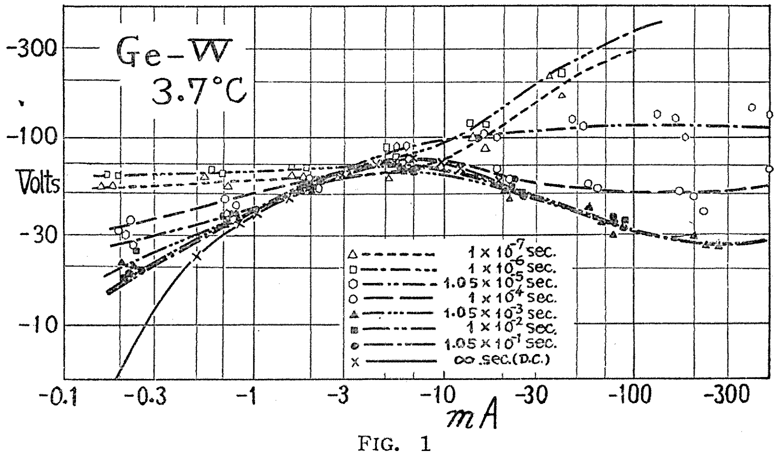

FIG. 1

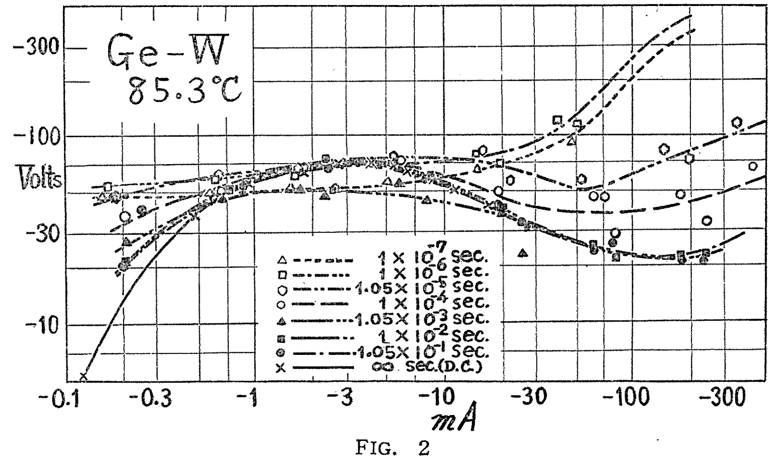

FIG. 2

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[f] Benzer S. **1949** J. Appl. Phys., 20, 804.

[g] Hunter L. P. **1951** Phys. Rev., 81, 151.

[h] Bennett A. I. and Hunter L. P. **1951** Phys. Rev., 81, 152.

rectifiers at 3.7 and 85.3°C respectively with the single pulsatory waves of various widths as shown in the figures. The broader the pulsatory widths, the interval of currents where the negative resistances lie, shifts to lower currents. These results will be explained with the adiabatic self-heating effect.

4. Cuprous oxide rectifiers

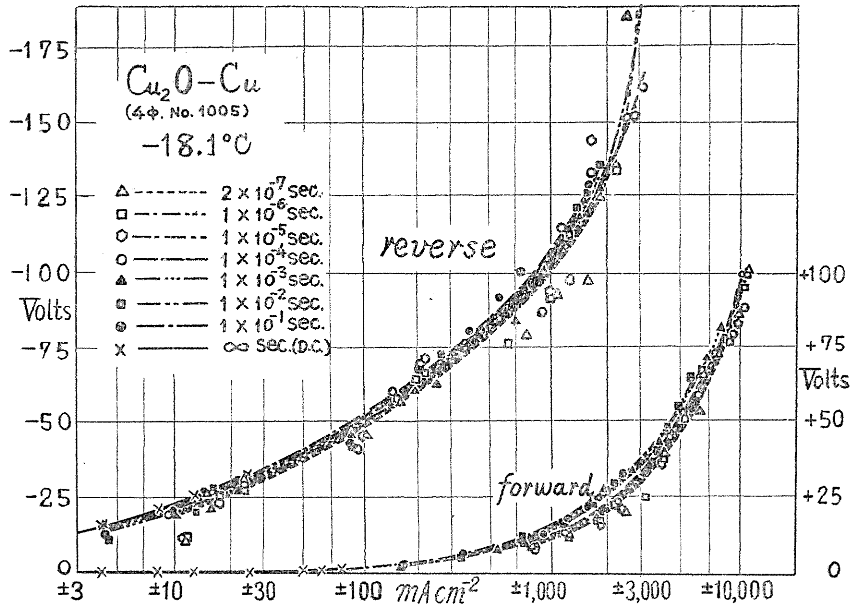

FIG. 3

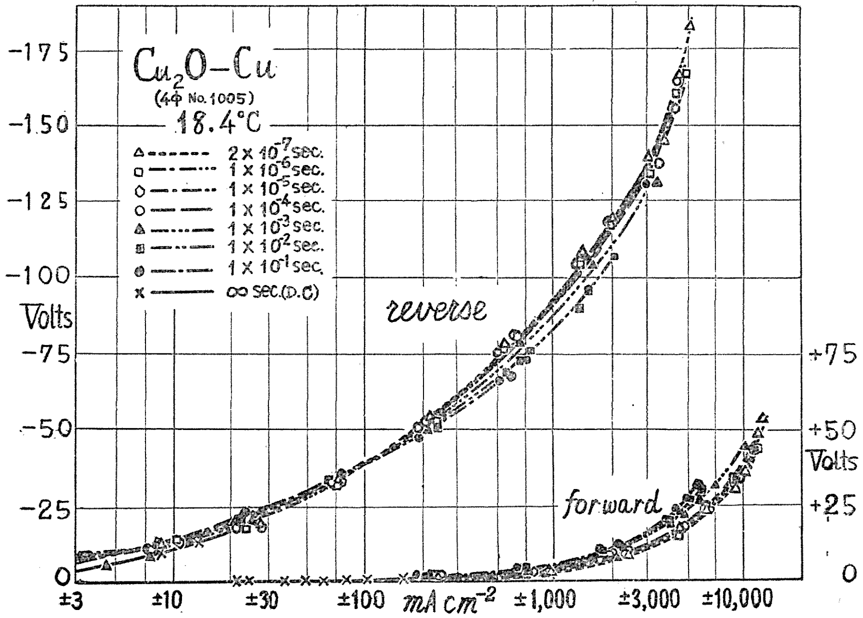

FIG. 4

Pulsatory measurements on the cuprous oxide rectifiers can be made at the temperature of below 140°C. The current-voltage relations at various pulsatory widths are shown in Fig. 3 and Fig. 4 at the temperature of -18.1 and 18.4°C respectively. At the temperature of about 140°C the conductivities of the rectifiers increases as results of the thermal effect, and at about 160°C the rectifiers breakdown completely, when both the forward and the inverse current-voltage relations completely coincide. It is remarkable that current-voltage curves are not influenced by the pulsatory widths as we can see from Fig. 3 and Fig. 4.

Fig. 5 shows the current-voltage curves at various temperatures at the pulsatory width of 10^{-5} second. At high inverse current densities, the curves nearly coincide. The dependences of the conductivity of the cuprous oxide rectifiers on the temperature almost disappear at high current densities, whereas the temperature dependences are normally large at low inverse bias voltages. Therefore, the activation energies are zero at high current densities and relatively larger at low current densities.

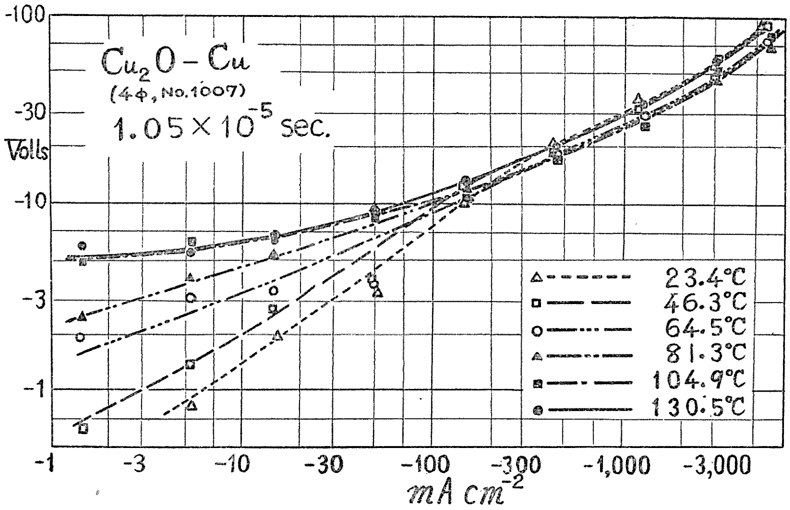

FIG. 5

The negative resistances can also be found in the cuprous oxide rectifiers at temperatures higher than room temperature and for the short pulsatory widths. Fig. 6 shows the negative resistance at 64.1, 81.9, 100.9 and 142.4°C. The negative resistances have not be observed yet at below room temperature. The interval of negative resistances shifts to higher current densities as the temperature rises.

5. Barium-coated selenium rectifiers

The electrical properties of the barium-coated selenium rectifiers are very different from those of the ordinally commercial selenium rectifiers. They are high-inverse voltage rectifiers, and one of their static characteristics is shown in Fig. 7. It is remarkable in the figure that the dependence of the current-voltage curves on temperature disappears at high current densities.

The current-voltage curves at various pulsatory widths are shown in Fig. 8, where the temperature is varied as −13.8, 0.0 and 12.5°C respectively. The temperature dependence of the current-voltage curves are not observed for the same pulsatory widths as shown in Fig. 9. The activation energies of the barium-coated selenium rectifiers are so small as we could not measure them.

The barium-coated specimens show sudden decrease of the bias voltages as

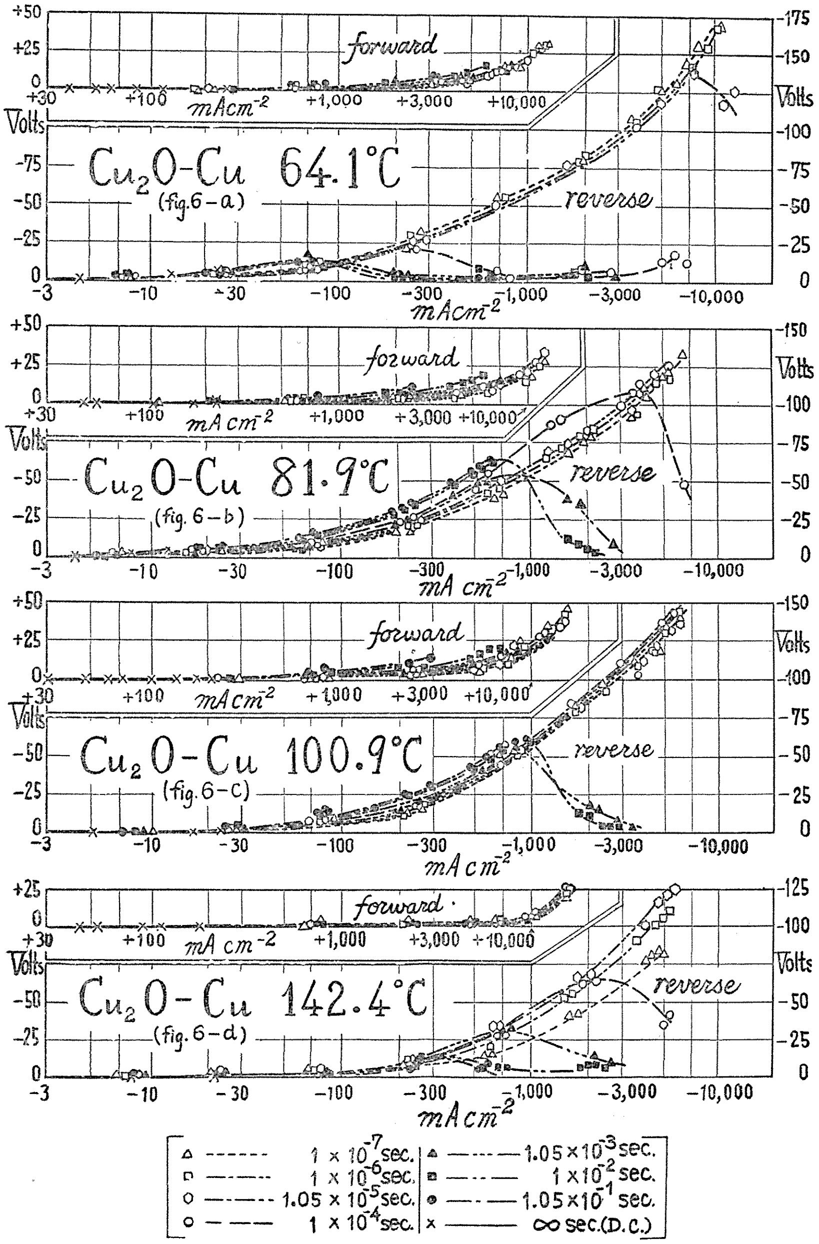

FIG. 6

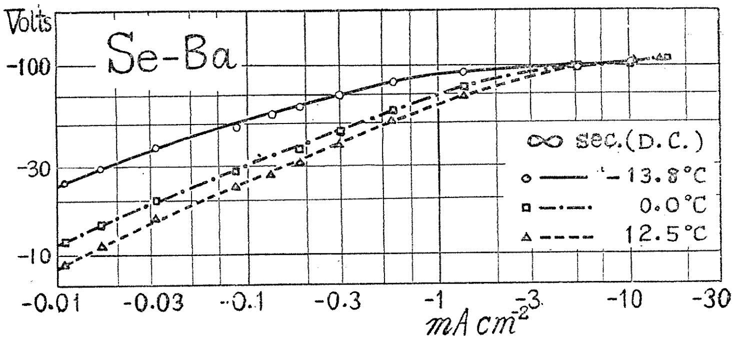
Volts
Se-Ba
-100
-30
-10
-0.01
-0.03
-0.1
-0.3
-1
-3
-10
-30
mA cm^-2
∞ sec.(D.C.)
○ —— -13.8°C
□ —·— 0.0°C
△ ---- 12.5°C

FIG. 7

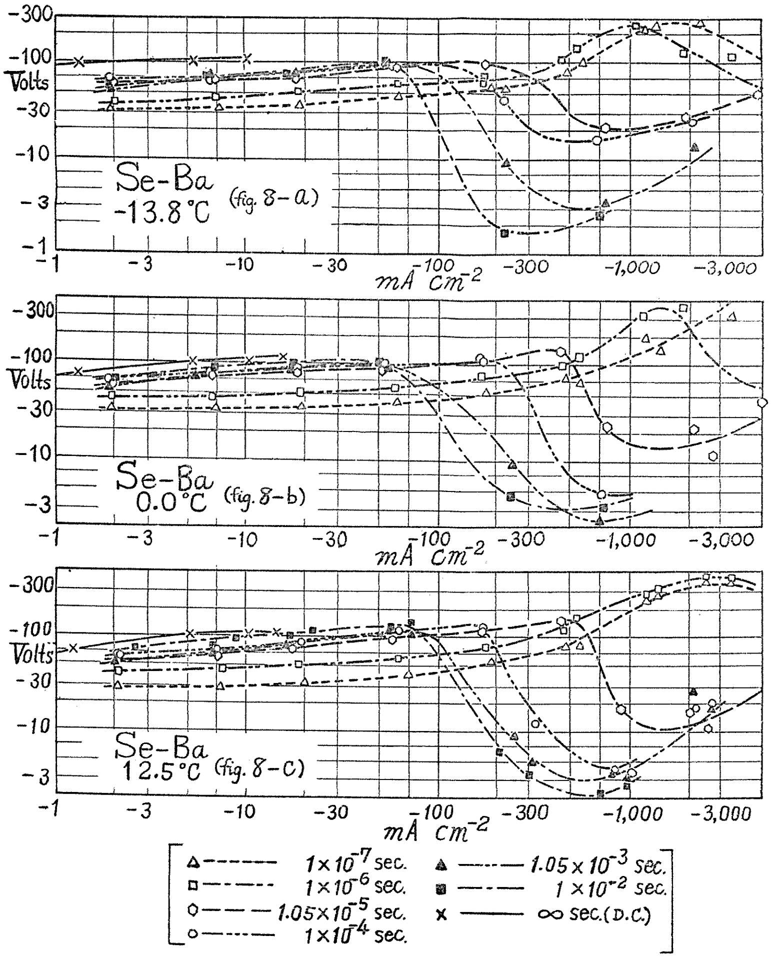
-300
-100
Volts
-30
-10
-3
-1
Se-Ba
-13.8°C (fig. 8-a)
-1
-3
-10
-30
-100
-300
-1,000
-3,000
mA cm^-2
Se-Ba
0.0°C (fig. 8-b)
Se-Ba
12.5°C (fig. 8-c)
△ ------ 1×10^-7 sec.
□ -·-·- 1×10^-6 sec.
⬡ —— 1.05×10^-5 sec.
○ -·-·- 1×10^-4 sec.
▲ -··- 1.05×10^-3 sec.
■ -·- 1×10^-2 sec.
× —— ∞ sec.(D.C.)

FIG. 8

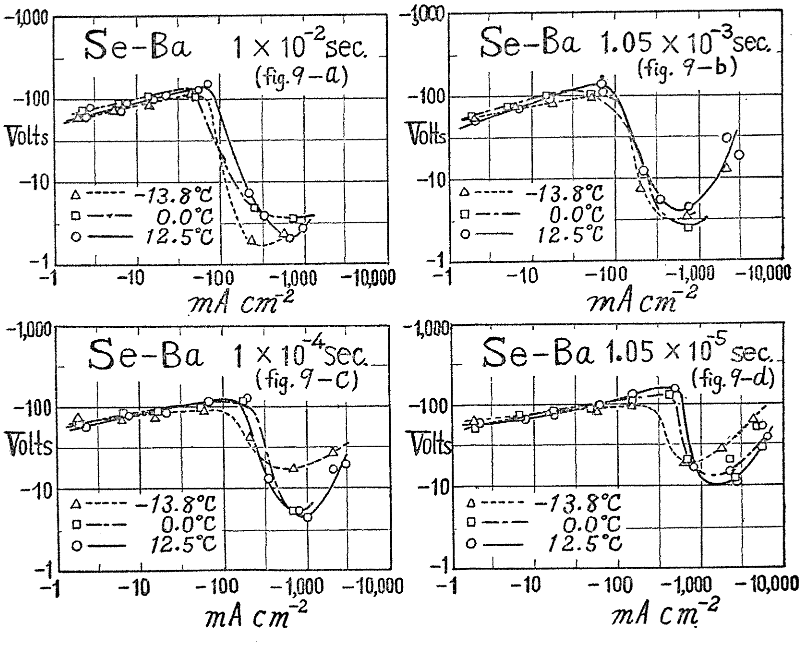

FIG. 9

the current densities exceed certain values which depend on pulsatory widths. The negative values of the resistance in the sudden decrease are very large as distinct from the germanium rectifiers, and it is imagined that the mechanism for the negative resistances are different from those of the germanium rectifiers.

6. Selenium rectifiers

Current-voltage curves of the selenium rectifiers are shown in Fig. 10 and in Fig. 11 at 3.3 and 37.0°C respectively. It is remarkable that the curves, whose pulsatory widths are broader than 10^{-4} sec., nearly coincide, whereas those of shorter than 10^{-5} sec., differ. This fact is reconciled with the fact that the selenium rectifiers have a dispersion frequency at about 10^6 cycles per sec.,[i] when the conductance v.s. frequency curves of the selenium rectifiers show a peak at the frequency.

As distinct from those of the cuprous oxide rectifiers, the current-voltage curves are not so much changed with the variation of temperature. The activation energies for the selenium rectifiers are much smaller than those for the cuprous oxide ones. Fig. 12 and Fig. 13 are those curves for the pulsatory widths of 1×10^{-4} and 1×10^{-6} seconds respectively.

As is the case for the cuprous oxide rectifiers, the curves under various temperatures become coincident as the current densities get larger. The curves become completely indeferent of temperature when the current densities exceed

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[i] Ono M. **1949** Memoirs of the Faculty of Engineering, Nagoya University, 1, 136.

1,000 mA cm^{-2}.

At these high current densities, the current-voltage relation deviates from Ohm's law; the currents increase more rapidly than the incrcase of the voltages. This fact tells us that the conductivity of the selenium rectifiers at high current densities is independent of temperature, and the mechanism of the conductivity is

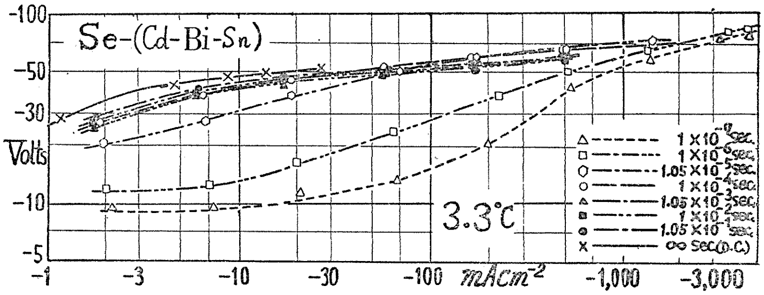

FIG. 10

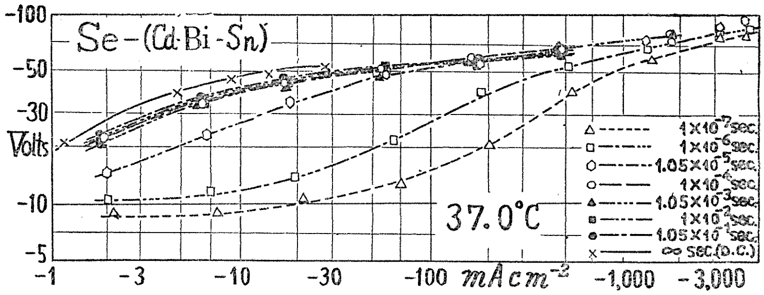

FIG. 11

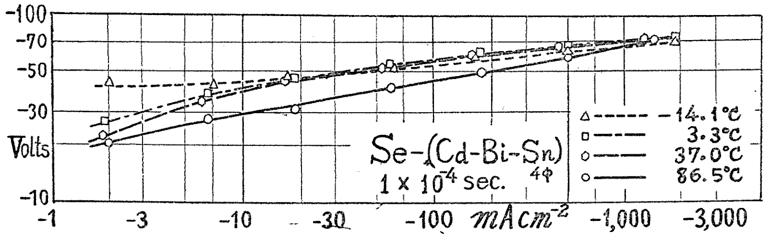

FIG. 12

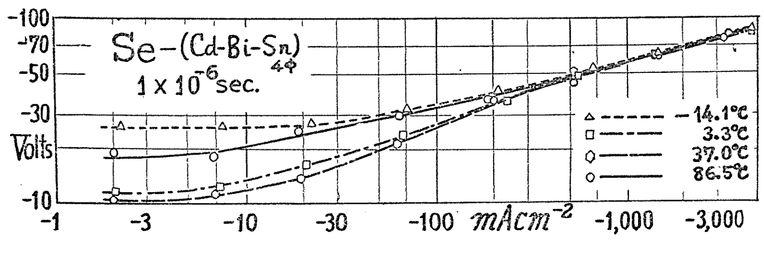

FIG. 13

governed by the phenomena which are the same as the ones which display a deviation from Ohm's law. The deviation from Ohm's law and the current-voltage curves independent of temperature would be caused by the direct excitation of electrons under the intense electric fields.

The above results are the case for the ordinally commercial selenium rectifiers having the electrodes of cadmium-bismuth-tin alloy. The negative resistances as was observed in the barium-coated selenium rectifiers are not observed. Negative resistances in the selenium rectifiers, however, are observed for the waves of broad pulsatory widths of about 10^{-2} and 10^{-3} sec. in the high-inverse voltage selenium rectifiers, where the electrical forming process is completely finished. Fig. 14 and Fig. 15 are the results got for such rectifiers at -15.4 and 1.7°C respectively.

The negative resistances in the selenium rectifiers are much larger than those for germanium rectifiers. It is the future problem why the negative resistances are observed for the high-inverse voltage selenium rectifiers such as barium-coated ones and completely formed ones.

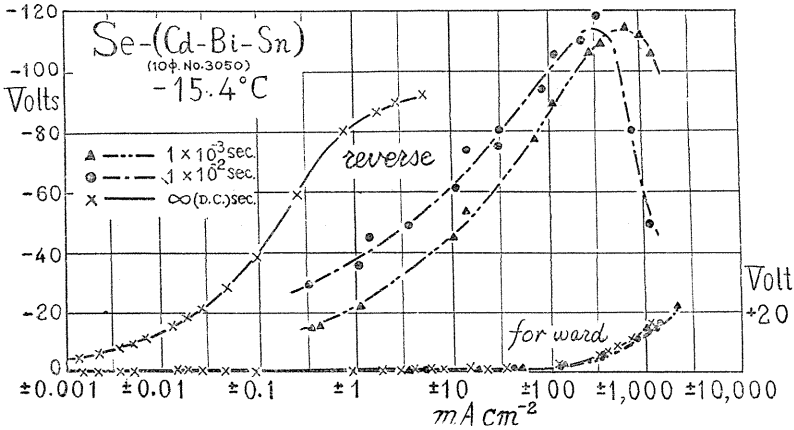

FIG. 14

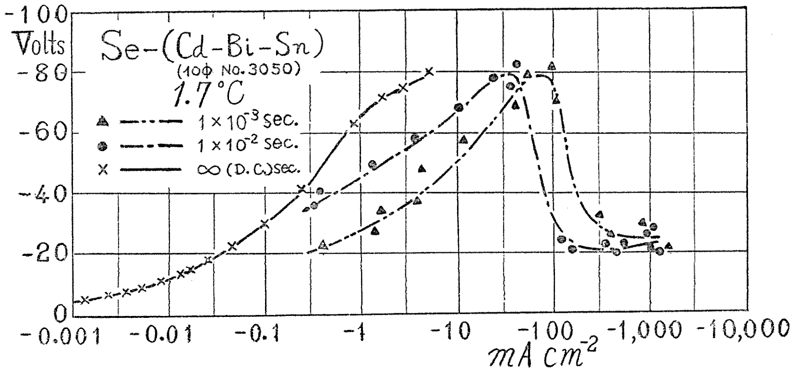

FIG. 15

7. Negative resistances in the rectifiers

We have get the negtive resistances not only for the germanium rectifiers but also for the high-inverse selenium rectifiers and the cuprous oxide rectifiers.

We have a doubt that all these negative resistances may be appreciated as the self-heating effect. Very large negative resistances are observed for the high-inverse selenium rectifiers. Slight dependences on temperature are observed to the rectifiers, by the static and pulsatory measurements of the current-voltage relations and by the high frequency impedance measurements.[i] Therefore the activation energies with the variation of temperature are very small, perhaps less than 0.1 electron volts. Therefore, temperature influences with the self-heating effect will be the same order as the germanium rectifiers, so we should have the small negative resistances as in the case of the germanium rectifiers.

It will be difficault to reduce the very large negative resistances such as in the barium-coated selenium rectifiers to the self-heating effect, although we have not enough quantitative evidences. These large negative resistances are so large as we wanted to reduce them to the new effect of a kind of the dielectric breakdown without destruction of the samples. New unsolved phenomena at high voltages near to the breakdown voltages have been reported. Joffe-Joffe[j] reported the fluctuations of the current at the high voltages. Henninger[k] also observed the decrease of the resistances near to the breakdown voltages. More enough experimental research is required to solve the problems at high current densities close to the breakdown phenomena.

8. The high-frequency dispersion of the rectifiers

In the previous paper[i] we got the dispersion of the dielectric constant and conductance in the selenium rectifiers. The dispersion frequency of the commercial selenium rectifiers is about 1.5 megacycles per second, and that of the barium-coated ones is about 50 kilocycles per second. The type of the dispersion curves is the Lawson's one, and the ionization theory is adequated for the selenium rectifiers, where the electrons are excited from the trapped impurity centres by phonons.

One phonon processes will be the case to fit the dispersion frequency above. Perhaps two phonon processes will have a dispersion frequency of the order of few seconds. It is needed for the one phonon processes that the activation energies are the order of kT at the measured temperatures, that is about 0.03 electron volts. As different from the activation energies got by the static measurements, we got small activation energies in the selenium rectifiers from pulsatory measurements, which is more smaller than 0.1 electron volt. This fact supports the one phonon processes.

High frequency dispersion measurements of the cuprous oxide rectifiers were got by several authors, when the dispersion frequency was about few kilocycles per second. It is remarkable that the current-voltage curves of static and pulsatory waves of various widths at the inverse voltages are nearlly the same as shown in Fig. 3 and 4. This fact is inconsistent with the results that there are dispersions in the cuprous oxide rectifiers. More precise impedance measurements will be needed of the cuprous oxide rectifiers, taking care that unfavourable influences such as

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[j] Joffe A. V. and Joffe A. F. **1940** Journal of Physics, 2, 283. cf. page 301.

[k] Henninger F. P. **1938** Phys. Z., 39, 216.

creep phenomena might not entre into the results of the experiments.

9. Creep of the semiconductor rectifiers

In the previous paper[1] the author measured voltage creep of the rectifiers, and got the following conclusions; (1) creep phenomena are not observed for the selenium rectifiers and the cuprous oxide rectifiers at low temperatures (below about 0°C) (2) voltage creep is observed in the cuprous oxide rectifiers at above room temperature, when the creep voltage is so changed that the conductance of the rectifiers changes gradually and continuously even when the current changes abruptly.

In the previous paper, the conductance is proportional to the number of electrons (n) in the conduction band, and n can be calculated as the equilibrium conditions, when n decreases with recombination of electrons, and increases with the excitation of electrons to the conduction band.

There are two types of the excitation of the electrons; the one is the excitation by phonons as reffered to 8, the other is the direct excitation with the strong electric fields.[b]

In the selenium rectifiers we assume that the former mechanism is predominate at low bias voltages than the latter. In this case, creep voltages are determined by the constant of the phonon excitations and that of the recombinations, and it is imagined that the voltage creep will decrease with the time constant of the order of the microseconds. So we could not observe creep in the time scale longer than microseconds. But at high inverse voltages the latter mechanism is more predominate than the former, because the former process is independent of voltage whereas the latter is strongly dependent on voltage as expressed with the bias voltage E by $\exp(-\beta/E)$.

In this case, time constant concerning the voltage creep will be equal to or smaller than in the case of the low bias voltages, because electron excitations are more frequent than at low bias voltages, whereas the recombinations are not so much changed.

In the cuprous oxide rectifiers, the energy gap between the top of the conduction band and the impurity level is about 0.4 electron volts at above room temperature, and about 0.7 electron volts at below about 0°C, and the activation energy is twice larger than at high temperature. Both energy gaps are too large to excite the electrons by the phonon processes. At low temperatures, direct excitation by the electric field is hardly possible. Direct excitation will occur at high temperature and at high current densities.

We can not get quantitative explanation about the creep phenomena in the cuprous oxide rectifiers because we do not know the numerical values of excitations and recombinations. Time rate of both the exitation and recombination mechanism is small in the case of the cuprous oxide rectifiers where the energy gap is very larger than that of the selenium ones.

We can say qualitatively that the difference of energy gap between the high and low temperature will be the fundamental origin for the difference of the creep phenomena between both temperatures.

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[1] Ono M. **1952** Memoirs of the Faculty of Engineering, Nagoya University, 4, 57.

10. Conclusions

Current-voltage relations of the semiconductor rectifiers are measured, with the single pulsatory waves of various pulsatory widths, over the wide range of current or current density and at various temperatures. Negative resistances are observed for all of the rectifiers. The results of the pulsatory measurements are not inconsistent with the impedance measurements at high frequencies and with the creep measurements.

We can conclude from the pulsatory experiments under sufficiently intense electric fields as follows; thermal ionization theory as was abopted in the present theories of rectifiers is unsatisfactory to the semiconductor rectifiers except at low bias voltages, and the electrostatic ionization theory is suitable for the rectifiers at high inverse voltages.

The author thanks to Mr. T. Nakayama for helping him with experiment.