THE ASYMMETRIC HEAT CONDUCTION OF SEMICONDUCTOR RECTIFIERS

I. F. Voloshin and N. M. Nedosekina

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We offer a survey of existing literature dealing with the problem of asymmetric heat conduction of semiconductor rectifiers, and we present the experimental results achieved by the authors of this article.

The transfer of heat in solids occurs in two ways: by means of free electrons, as well as by means of longitudinal and transverse waves of elastic oscillations within the crystal lattice [1].

The concentration of free electrons in semiconductors is small. Consequently, only a small fraction of the heat can be transmitted by the electrons, with the greater portion of the heat being transmitted by elastic waves.

Researchers have repeatedly dealt with the problem of the role played by free electrons in the phenomenon of heat transfer in solids, particularly with regard to semiconductors. Cuprous oxide has been the subject of particularly intensive investigation. In reference [2] Vogt used theoretical calculations to draw the conclusion that the electron portion of the heat conduction in cuprous oxide is virtually undetectable. Despite this conclusion, Amirkhanov [3] again took up this problem, proceeding from the theoretical statements of Davydov and Shmushkevich [4] to the effect that the presence of "comparable" amounts of electrons and holes may have a significant effect on the heat conduction of a semiconductor. However, the extensive studies carried out by Amirkhanov only served to confirm Vogt's conclusion. The problem of the role played by free electrons in heat transfer is closely related to the similar theoretical scientific problem of the unipolar heat conduction of a rectifier. The actual possibility of this phenomenon is based on the fact that the barrier layer of the rectifier (the p-n junction) represents a potential barrier across the path of charge motion.

Since the magnitudes of the electrical resistance of the p-n junction are functions of the direction of motion for the charges forming the electrical current, there must exist an optimum direction for heat transfer as well, since the charges possess kinetic energy while in motion, and this energy can be seen in the phenomenon of heat transfer. This means that the thermal conductivity of the rectifier must vary for different directions of the heat flow. Consequently, heat flows—identical in magnitude but different in direction—will set up diverse temperature gradients in a rectifier.

It is the possibility of such asymmetry in heat transfer through a rectifier that had been pointed out by Ioffe. At this suggestion, the Leningrad Physicotechnical Institute undertook a project [5] whose purpose was to check the role of free electrons in the phenomenon of heat conduction, using a copper-oxide rectifier in the research. It was assumed that the thermal conductivities of the rectifier should be different for the various directions of the heat flow, and that only the resistance of the barrier layer could result in an asymmetric coefficient of thermal conductivity. The project did not lead to the anticipated result: no differences were detected in the thermal conductivities of the barrier layer. It is Nelidov's [5] conclusion that additional research is required into the role of the barrier layer in the phenomenon of heat transfer.

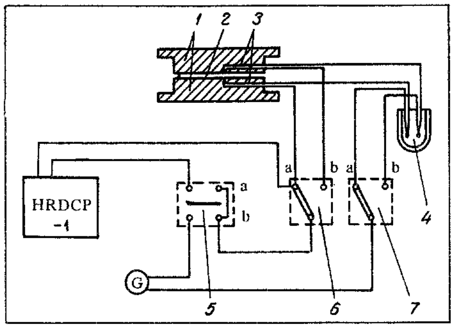

Fig. 1. Block and electrolytic diagrams of installation measuring thermal electromotive force of plate rectifiers: 1) metal heaters; 2) sample under study; 3) thermocouples; 4) vacuum flask; 5) tumbler; 6, 7) switches; G is the galvanometer; HRDCP is the high-ohmic dc potentiometer.

Starr [6] also dealt with this problem in 1936. He was able to detect the asymmetric heat conduction of a copper-oxide rectifier in the course of an experiment.

Subsequently, Amirkhanov [3], investigating the thermal conductivity of cuprous oxide, additionally raises the question as to the asymmetry of heat conduction in a copper-oxide rectifier. However, the author was unable to detect this effect within the limits of accuracy for his installation, employing two oppositely directed heat flows.

Finally, in 1951 Horn [7] again returned to the problem of the heat conduction of a copper-oxide rectifier. Horn carried out a series of precise measurements and it is his contention that within a 10% limit of error no asymmetry could be detected in the heat conduction of a copper-oxide rectifier. Analyzing Starr's experiments, Horn assumes the reasons for the positive results achieved by Starr in the study of this effect to have been the fact that he employed an improper procedure to connect the thermocouples used to measure temperature. Starr used differential thermocouples, and since reference [6] makes no stipulation with regard to the electrical insulation of the thermocouple junctions from the rectifier, the results of this experiments on the measurement of temperature differences might have been affected by the thermoelectrical properties of the rectifiers.

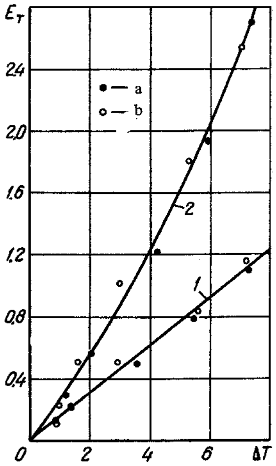

Fig. 2. Thermal electromotive force E_T (mV) versus temperature drop ΔT(°K) across planes of copper-oxide (1) and selenium (2) rectifiers: a) thermal electromotive force with straight heat flux; b) the same with reverse flow.

A study of the literature on research in this field leads to the conclusion that direct measurement of the thermal conductivity of a copper-oxide rectifier provides no opportunity to determine asymmetry in these magnitudes, given two oppositely directed heat flows and a permanently fixed rectifier.

The effect of thermal rectification in a semiconductor wafer was discovered in the course of Amirkhanov's research [8]. This essentially involves the fact that a wafer of an extrinsic semiconductor—in a heat field—acquires the characteristics of a rectifier. The theoretical possibility of this effect was confirmed by Tolpygo and Tsidil'kovskii [9], as well as by Tauc [10]. The magnitude of this effect is quite insignificant; its experimental measurement is barely possible. The effect of asymmetric heat conduction can be regarded as the opposite of thermal rectification. In other words, theoretically it is possible to have asymmetry in the heat conduction of a rectifier, but because the fraction of the free electrons in the heat conduction is small in comparison with the fraction participating in the conduction of heat from the lattice, we are unable to measure this effect with any of the means known to us.

Since the hypothesized asymmetry is a result of the action of the barrier layer (of the p-n junction) of the rectifier to block the passage of charges, we decided to measure the thermal emf of the rectifier to evaluate the asymmetry.

We know that if a temperature gradient is set up in a conductor, a thermal emf will appear at its ends. This is a result of diffusion of the mobile current carriers from that portion of the body exhibiting the higher temperature to those regions of the body which are cooler; the change in the direction of the heat flow causes the sign of the thermal emf to change. If the action of the p-n junction affects the diffusion carrier flow, this should result in various thermal emf's for the different directions of the heat flow.

To measure the thermal emf's of wafer semiconductor rectifiers, we set up an experimental installation (Fig. 1) [12] to produce the temperature gradient along the specimen and to measure it.

The research was carried out on conventional copper-oxide and selenium rectifier disks. The thermal emf's (E_T) of the rectifiers as a function of the temperature differences ΔT on their planes for two oppositely directed heat flows is shown in Fig. 2. For ease of comparison, the forward and return branches with the various signs of the characteristic $E_T = f(\Delta T)$ have been placed on a single graph. As the figure shows, the absolute magnitudes of the thermal emf's can be regarded as being coincident when the direction of the heat flow changes.

The maximum magnitude of the thermal emf obtained in the rectifier studies for the given temperature differences does not exceed 3–5 mV. At these voltages, the current-voltage characteristic of the rectifier is symmetrical; the asymmetry appears on application of a voltage in excess of 10 mV.

Consequently, all of the measurements were carried out on the symmetrical portion of the current-voltage characteristic of the rectifier. It is obvious that this is the reason for the absence of asymmetry in the thermal emf's at the rectifier output with a change in the direction of the heat flow.

Similar measurements were carried out for a series of copper-oxide and selenium rectifiers. The results agree with those described above.

To determine the heat conduction of the rectifier, we added two identical nickel units (45 mm in diameter and 6 mm in thickness) to the installation described above, and differential thermocouples were imbedded in these nickel blocks. The thermocouples

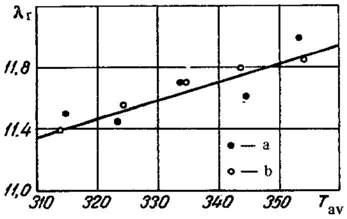

Fig. 3. Temperature dependence of thermal conductivity coefficient λ_r for copper-oxide rectifier W/m · deg) with heat flux directed from semiconductor layer to backing material (a) and backward (b).

were passed through milled grooves in the surfaces of the blocks. The width and depth of the grooves was determined by the thickness of the wire used to make the thermocouples. The test rectifier was positioned between the nickel blocks; a thin layer of glycerine was applied to the surface of the rectifier. This entire system was positioned in the installation shown in Fig. 1. A heat flow was generated and the temperature differences across the nickel blocks and across the rectifier were measured. To avoid the influence of thermoelectric effects on the magnitudes of the measured temperature differences, one of the junctions from each of the differential thermocouples was electrically insulated from the object being measured. The thermal conductivity for the nickel was taken from tables and found to be equal to 58 W/m · deg. The specific heat flows q_1 and q_2 through the nickel blocks were calculated. Neglecting the lateral heat losses, we found the magnitude of the heat flow through the rectifier to be $q_{av} = (q_1 + q_2)/2$. The thermal conductivity of the rectifier was calculated to be $\lambda_r = q_{av} d_r/\Delta T$. The maximum measurement error for the temperature differences found with the potentiometer did not exceed 3.5%. The maximum measurement error for the thermal conductivity of the copper-oxide rectifier did not exceed 11%.

Figure 3 shows an experimental curve for the thermal conductivity of the copper-oxide rectifier as a function of temperature in the case of two oppositely directed heat flows. In processing the experimental data, we employed the method of least squares [11]. The maximum deviation in the experimental points from the approximating curve is less than 1.5%.

As we can see from Fig. 3, within the limits of maximum measurement error (11%), no asymmetry in the thermal conductivity of a copper-oxide rectifier was found.

NOTATION

E_T is the thermal electromotive force of the rectifier, mV; ΔT is the temperature drop across the rectifier, °K; q_1 and q_2 are the specific heat flows through the nickel blocks, W/m^2; q_{av} is the specific heat flux through the rectifier, W/m^2; d_r is the rectifier thickness, m; λ_r is the thermal conductivity of the rectifier, W/m · deg.

REFERENCES

1. A. F. Ioffe, The Physics of Semiconductors [in Russian], Izd. AN SSSR, Moscow, 1957.
2. W. Vogt, Ann. der. Phys., B 7, 186, 1930.
3. Kh. I. Amirkhanov, Izv. AN AzSSR, vol. 1, no. 4, 1946.
4. B. I. Davydov and I. M. Shmushkevich, UFN, vol. XXIV, no. 1, 1940.
5. I. Yu. Nelidov, ZhETF, 2, no. 4, 1932.
6. C. Starr, Physics, 7, no. 1, 1936.
7. F. H. Horn, Journ. Appl. Phys., 22, 9, 1951.
8. Kh. I. Amirkhanov, Izv. AN SSSR, ser. fizich., 5, no. 4–5, 1941.
9. K. B. Tolpygo and I. M. Tsidil'kovskii, ZhTF, 22, no. 9, 1952.
10. J. Tauc, Czechosl. Journ. Phys., 6, 1956.
11. K. P. Yakovlev, The Mathematical Processing of Measurement Results [in Russian], GITTL, Moscow-Leningrad, 1950.
12. N. M. Nedosekina and V. E. Ulashchik, Thermoelectrical Measurements and Monitoring [in Russian], Izd. Nauka, 1967.

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Institute of Heat and Mass
Transfer AS BSSR, Minsk