

transition region was reported in Refs. 2 and 3. In the case of our Raman spectra there was no hysteresis. Possibly this effect could be observed by a more precise determination of the ratio of the line intensities and their frequencies as a result of a change in temperature.

Our results therefore demonstrated that phase transitions in CdP_2 resulted in small changes in the frequency ($<0.5 \text{ cm}^{-1}$) of the Cd-P vibrational modes and large changes in the frequencies ($\sim 0.5\text{--}1 \text{ cm}^{-1}$) of the Davydov multiplets. The phase transitions influenced strongly the polarization dependences of the Davydov multiplets.

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Changes in the mechanisms of the current flow across a contact between Au and *p*-type InAs due to proton implantation

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A study was made of the influence of the proton implantation dose on the current-voltage characteristic of a contact between Au and *p*-type InAs. The influence was nonmonotonic because the initial accumulation of electrically active defects suppressed the tunnel components of the current and reduced the efficiency of avalanche multiplication under reverse bias voltages, which in turn improved the rectifying properties of the contact. A further increase in the density of states in the band gap on increase in the implantation dose gave rise to conduction involving these states and transformation of the contact into an ohmic one.

In a previous investigation of contacts between Au and *p*-type InAs we found¹ that proton implantation provided an effective means for the control of the properties of such contacts, which could be used both to improve their rectifying characteristics and to form ohmic contacts. A detailed analysis of the temperature dependences of the current-voltage characteristics and its derivatives was reported in Ref. 2 for unimplanted Au-*p*-InAs contacts with the hole density $p = (6\text{--}7) \times 10^{16} \text{ cm}^{-3}$, which made it possible to determine the current flow mechanisms in a structure of this kind. In particular, two-stage tunneling was observed against the background of a thermionic current; this was observed earlier only in the case of heavily doped InAs with $p \approx 1 \times 10^{18} \text{ cm}^{-3}$ (Refs. 3 and 4). This type of tunneling began only at some specific temperature because of the relatively low potential barrier ($\varphi_B = 0.38 \text{ eV}$) characteristic of the contact fabrication technology proposed by us.^{1,2} It was also found that the surface states influenced charge transport. In the present paper we shall report a similar analysis for Au-*p*-InAs contacts [$p = (6\text{--}7) \times 10^{16} \text{ cm}^{-3}$], which were implanted with 150-keV protons. The following proton doses were used: 10^{11} , 10^{12} , and 10^{13} cm^{-2} . The technology of fabrication of these structures was the same as in Refs. 1 and 2. A mesa

structure formed as a result of irradiation did not alter the current-voltage characteristic. Consequently, the leakage along the implanted surface not occupied by the metal electrode had no significant influence on the results of our measurements.

As pointed out above, the main feature of the original contact was the appearance of two-stage tunneling during heating, which was manifested by a maximum in the voltage dependence of the conductivity (see Fig. 3 in Ref. 2). Similar dependences for the implanted samples were obtained in the present study (Fig. 1) and they showed that an analogous maximum was observed also after implantation doses of 10^{11} and 10^{12} cm^{-2} . A comparison with an unirradiated sample showed that implantation suppressed partly the process of two-stage tunneling. This was due to a change in the transparency of two potential barriers responsible for this process. The transparency of the first barrier (due to the insulating gap between the metal and an *n*-type inversion layer) increased as a result of implantation, whereas the transparency of the second barrier (representing the space charge region of the semiconductor) decreased because of an increase in the width of this region due to compensation of *p*-type InAs by donor states of the radiation defects.

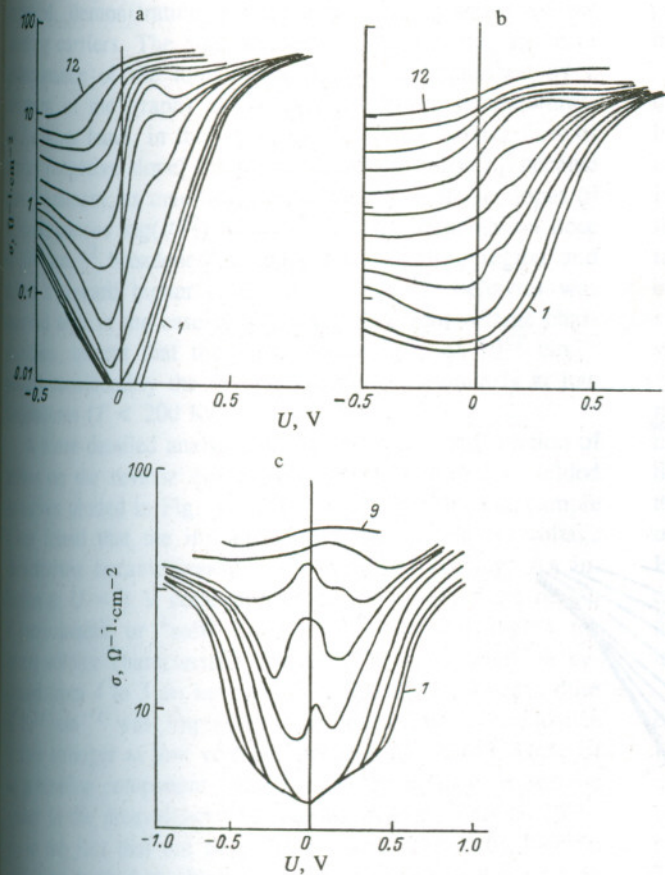


FIG. 1. Conductivity of an Au-p-InAs contact recorded as a function of the voltage after different implantation doses D . a) $D = 10^{11} \text{ cm}^{-2}$; T (K): 1) 78, 2) 109, 3) 130, 4) 155, 5) 176, 6) 194, 7) 210, 8) 229, 9) 244, 10) 259, 11) 271, 12) 298. b) $D = 10^{12} \text{ cm}^{-2}$; T (K): 1) 78, 2) 118, 3) 145, 4) 166, 5) 178, 6) 196, 7) 211, 8) 229, 9) 245, 10) 259, 11) 273, 12) 298. c) $D = 10^{13} \text{ cm}^{-2}$; T (K): 1) 78, 2) 109, 3) 133, 4) 173, 5) 209, 6) 229, 7) 244, 8) 260, 9) 273.

One should mention also that in the case of an unimplanted sample at low temperatures and under forward bias voltages the voltage dependence of the conductivity exhibited a slight inflection (Ref. 2) representing a distribution on the energy scale of the density of states participating in the tunneling process. Implantation destroyed this inflection. In the case of the original sample the conductivity curves recorded at low temperatures (77-120 K) were practically independent of temperature, whereas after implantation they did vary with temperature. This demonstrated that the initially dominant tunneling process became less important as a result of implantation and that the influence of the states at the metal-semiconductor interface also became weaker.

The conductivity curves obtained after implantation with a dose of 10^{13} cm^{-2} were quite different. They were practically symmetric relative to zero bias voltage and in the temperature range from 77 to 170 K these curves merged into a single line at low bias voltages. A further increase in the temperature of a sample gave rise to a maximum at zero bias voltage. The amplitude of the maxima, measured relative to the bottom of the "valleys," first rose with temperature and then the maximum began to flatten and already at temperatures $T \geq 260 \text{ K}$ the conductivity became practically independent of the applied voltage and the contact changed to ohmic.

Obviously, implantation of a proton dose of 10^{13} cm^{-2} created a disturbed surface layer where there were many levels with different energies within the band gap. The trans-

port of charge in such a system could be due to variable-range hopping between localized states in the band gap (assisted by phonons or by the field effect) or due to diffusion and drift, if the impurity levels broadened and overlapped the edges of the band gap on increase in temperature.⁵ The dependences suggested that the field effect predominated at low temperatures, but as the voltage (causing electron heating) was increased, this was supplemented by phonon-assisted hopping conduction. The existence of a minimum in the case of the conductivity curves recorded at high temperatures could be due to the heating of carriers or a change in the cross section of the scattering by defects, depending on the electron energy.

We shall now consider the temperature dependences of the current under a forward bias of $V = 0.4$ volts (Fig. 2). The scale along the ordinate $-\log(I/T^2)$ was selected so as to separate the above-barrier mechanism of the flow of the current due to thermionic emission from the tunnel mechanism characterized by a weak temperature dependence. The former corresponded to a region with a negative slope, which was observed at high temperatures, whereas the latter was characterized by a region with a slight positive slope at low temperatures. An estimate of φ_B from the band gap (E_g), obtained for a temperature at which two-stage tunneling appeared, gave the value 0.395 eV for the samples which received the implanted-proton doses of 10^{11} and 10^{12} cm^{-2} , whereas for the original sample we found that $\varphi_B = 0.38 \text{ eV}$.

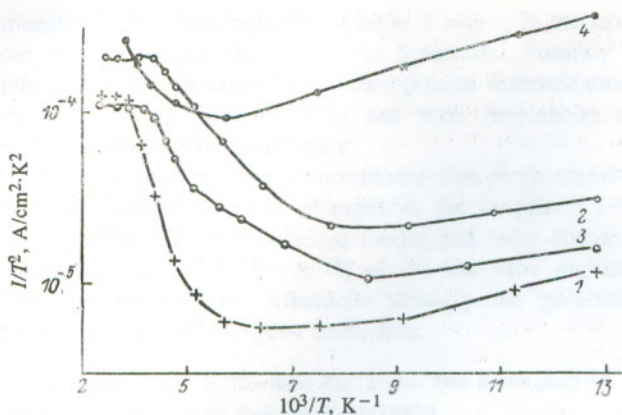


FIG. 2. Temperature dependence of the current observed under a reverse bias voltage of $U = 0.4$ V. D (cm^{-2}): 1) 0; 2) 10^{11} ; 3) 10^{12} ; 4) 10^{13} .

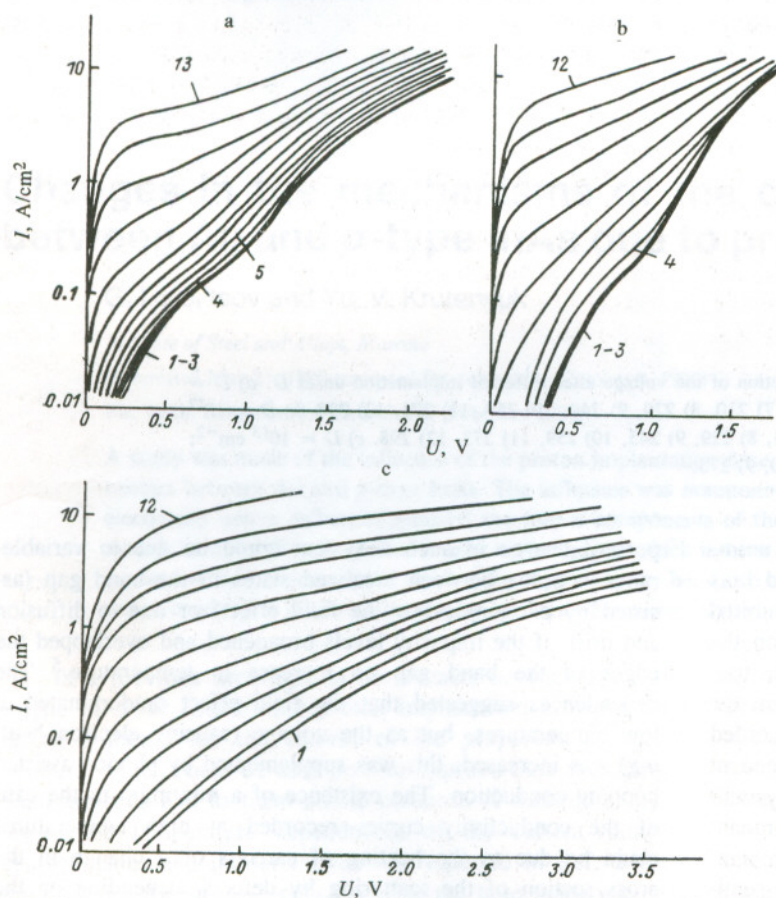


FIG. 3. Reverse current-voltage characteristic of an Au-p-InAs contact. a) $D = 0$; T (K): 1) 77, 2) 89, 3) 110, 4) 133, 5) 156, 6) 175, 7) 194, 8) 211, 9) 229, 10) 244, 11) 259, 12) 273, 13) 298. b) $D = 10^{11}$ cm^{-2} . c) $D = 10^{12}$ cm^{-2} (the temperatures for the curves in Figs. 3b and 3c are exactly the same as in Figs. 1a and 1b).

An increase in the barrier height in the case of the irradiated samples agreed with an increase in the transparency of the intermediate insulating gap, but not with the reduction in the slope of the high-temperature parts of curves 2 and 3 in Fig. 2. This behavior could be explained by an increase in the fraction of the tunneling electrons at high temperatures. In the case of the implanted samples the two-stage tunneling appeared in the conductivity graph as an inflection, which then transformed to a maximum but at a higher temperature than in the initial state. This temperature increased with the im-

plantation dose. This was evidence of an increasing degree "smearing" of the edges of the band gap and a consequent smearing of the potential barrier in the implanted samples. This effect broadened the part of the current-voltage characteristic where the current-flow mechanism was due to thermionic emission and also due to the tunnel effect in the implanted contacts. The graphs plotted in Fig. 2 could be used to judge the degree of dominance of this or other mechanism. For example, when the dose was increased to 10^{12} cm^{-2} , the positive slope of the low-temperature parts of the curves

increased, demonstrating a reduction in the fraction of the tunneling carriers. The high-temperature limit of the region of predominance of the tunnel mechanism (characterized by a minimum in the graph) shifted toward lower temperatures. On the other hand, in the region of the above-barrier flow of carriers (negative slope) the influence of the tunneling became more prominent, as manifested by a reduction of the slopes of the dependences $\log(I/T^2) = f(10^3/T)$. The implantation dose of 10^{13} cm^{-2} broadened strongly the tunneling region and shifted it toward higher temperatures. Similar behavior was observed also in the case of the reverse current-voltage characteristics, except that the implantation dose of 10^{12} cm^{-2} reduced considerably the reverse currents, particularly at low temperatures ($T < 200 \text{ K}$).

A more detailed analysis of the results of implantation of protons on the reverse current-voltage characteristics yielded the curves plotted in Fig. 3. In the case of the original sample it was found that the influence of T on the current-voltage characteristic became weaker as a result of cooling. An inflection at $U = 1 \text{ V}$ corresponded to the onset of the region of preavalanche or "soft" breakdown.^{2,6} In this region the current-voltage characteristic obeyed $I \propto U^m$, where m decreased from 4 to 3 on increase in temperature. When a dose of 10^{11} cm^{-2} was implanted, the temperature dependence became stronger at low voltages because of predominance of the generation component, whereas at high voltages it became weaker in the preavalanche breakdown region. This could be due to the fact that not only the carriers created by thermal generation reached the high-field region, but also those which tunneled across the barrier whose transparency increased because of the participation in the tunneling of the states formed as a result of implantation. The electrons which tunneled across also participated in the avalanche multiplication in the space charge region. On increase in temperature, which reduced the mean free path of electrons, a higher voltage was needed to induce the avalanche process. An increase in the voltage increased not only the accelerating field, but also the number of the carriers that penetrated by the tunnel effect to the space charge region and participated in the impact ionization processes. Since at high reverse voltages a sample implanted with a dose of 10^{11} cm^{-2} exhibited a current-voltage characteristic which was independent of temperature, we concluded that the main contribution in the prebreakdown region was in this case made not by the electrons formed by thermal generation, but those which penetrated by the tunnel effect to the space charge region and were then accelerated and participated in the avalanche multiplication processes.

A further increase in temperature resulted in quite a strong reduction in the mean free path which suppressed the impact ionization and this was manifested by suppression of an inflection in the graphs. At temperatures $T > 210 \text{ K}$ the

current-voltage characteristic exhibited an activated-type dependence.

The 10^{12} cm^{-2} dose suppressed an inflection typical of the preavalanche breakdown. The absence of the preavalanche breakdown region was the main cause of the reduction of the current under negative bias voltages in excess of 1 V. Therefore, at this dose the concentration of defects was sufficient to reduce the mean free path sufficiently for the avalanche multiplication of carriers to be suppressed completely. In the case of these samples the breakdown at 77 K was observed under a reverse bias of up to 10 V. Moreover, this dose suppressed strongly the tunneling of electrons.

The defects created by implantation had a tendency to migrate deeper into the semiconductor.⁷ Therefore, the distribution profile of the electrically active levels associated with these defects was quite smooth and its gradient was less than that in the case when a $p-n$ junction was formed by diffusion or implantation of impurities. Theoretical estimates and the Hall effect measurements indicated that the dose of 10^{12} cm^{-2} was necessary for the compensation of InAs with $p = 6 \times 10^{16} \text{ cm}^{-2}$. The nature of the current-voltage characteristic confirmed this.

We therefore drew the following conclusions about the effects of proton implantation on the properties of Au- p -InAs Schottky barriers. When the dose was increased to 10^{12} cm^{-2} , accumulation of electrically active centers of the donor type occurred in the surface layer and this altered the shape of the potential barrier and the mean free path in this layer. The structure was then a complex combination of a Schottky barrier, a $p-n$ junction, and a transition layer between them. The formation of defects by implantation of the 10^{13} cm^{-2} dose gave rise to conduction involving defect levels and in this case the potential relief had no significant influence on the flow of the carriers.

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