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ELECTRON TRANSFER EFFECT IN INTRINSIC TELLURIUM SINGLE CRYSTALS

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Résumé.- Des recherches expérimentales et théoriques concernant le transfert des porteurs et les effets des porteurs chauds en tellure intrinsèque ont été effectuées. Les caractéristiques courant – tension enregistrées au moyen de la technique des impulsions nanosecondes indiquent une resistance différentielle, si l'intensité du champ dépasse une valeur de 3.5 kV/cm.
A l'aide de sondes électriques des domaines mouvants de champs intensifs ont été mis en évidence.
La vitesse de dérive monte à $7 \cdot 10^6$ cm/s.
Le champ seuil et le coefficient de Hall ont été mesurés aux températures élevées et à une pression hydrostatique. Les résultats indiquent l'existence d'une deuxieme bande de conduction, qui se trouve 0.26 – 0.38 eV au-dessus de la premiere bande, et avec une mobilité des porteurs relativement faible.
Les valeurs du champ seuil et de la mobilité électronique, obtenues selon la méthode Monte-Carlo, correspondent bien aux valeurs expérimentales..

Abstract.- Experimental and theoretical studies of charge transport and hot carrier effects have been made in intrinsic tellurium. Pulse measurements of current-voltage characteristics have shown a negative differential resistance at fields above 3.5 kV/cm. Moving high-field domains were observed by potential probe measurements. The velocity of the domain was $7 \cdot 10^6$ cm/s. Hydrostatic pressure measurements of threshold field and Hall coefficient were performed at elevated temperatures, which suggest the existence of a second, low mobility conduction band located 0.26 – 0.38 eV above the first one. Reasonable agreement was obtained between the measured magnitudes of threshold field and electron mobility and the results of Monte Carlo calculations.

1. Introduction.- Semiconducting tellurium always shows p-type conduction in the extrinsic range. Therefore, the investigation of the conduction electron properties is possible in the intrinsic conduction range only. Recent experimental investigations of high field transport in intrinsic tellurium shows that the current-voltage characteristics exhibits a voltage-controlled negative differential resistance (n.d.r.) at fields above 3.5 kV/cm /1/. The present work deals with a further examination of this effect. The measurements of

current-voltage characteristics and Hall effect were made under hy-
drostatic pressure to obtain information about the nature of n.d.r..
Monte Carlo calculations have also been carried out using the most
probable values of parameters in order to explain the experimental
results.

2. <u>Sample preparation</u>.- The samples investigated were cut from Te
single crystals with a hole concentration of $5 \cdot 10^{14}$ cm^{-3} and a mobil-
ity of 5000 cm^2/Vs at 77 K parallel to the c-axis. They were dumbbell
shaped to eliminate the influence of electron extraction in the near-
cathode region. The field distribution along the sample was measured
using two gold wire potential probes. The first one was alloyed to
the middle thin part of the sample. The voltage of this probe was
the basic potential. The second wire was pressed to the sample at
various distances from the alloyed probe.

3. <u>Measurements at atmospheric pressure</u>.- Fig. 1 shows current -
voltage characteristics measured under atmospheric pressure at vari-
ous temperatures and 5 ns after pulse beginning. A voltage controlled
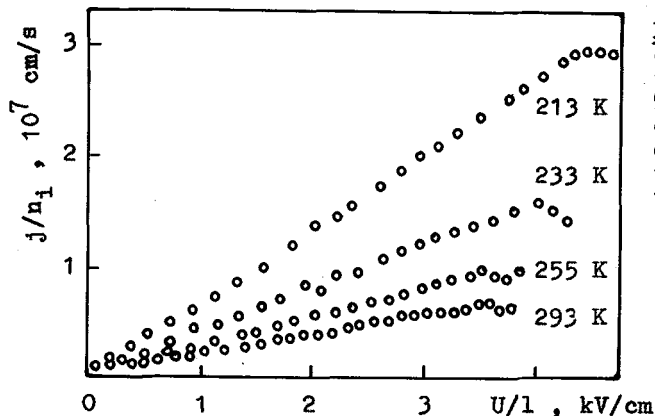

Fig. 1: Current-voltage
characteristics of in-
trinsic tellurium sample.
The current density is
divided by the intrinsic
carrier concentration at
the corresponding
temperature.

n.d.r. is observed at electric field strengths above 3.5 kV/cm. It
must be noted that no superohmic increase of the current was detected
at fields below the threshold of n.d.r., which would be typical for
impact ionization. The current pulses show a single kink as the field
is just at the threshold. Oscillations can be observed on the growing
current when the field is increased further. The n.d.r. exists in the
intrinsic conduction range only. No n.d.r. was observed at 183 K
where hole conduction prevails /1/. In /1/ it is shown that a high
field domain is formed at the threshold of n.d.r.. We made potential
probe measurements to establish the velocity of the domain. The po-

tential pulses measured at 225 K are shown in fig. 2. The shape of the pulses shows that the high field domain propagates in the sample in the direction toward the anode with a velocity of $7 \cdot 10^6$ cm/s. The direction of this propagation as well as the disappearance of n.d.r. at low temperatures in the hole conduction range gives evidence that the n.d.r. is connected with conduction electrons. The field and time range in which the instability is observed suggest that the most probable cause of this effect is an electron transfer to a higher lying conduction band. A classical test for the electron transfer model is the hydrostatic pressure experiment. Therefore, we made investigations under hydrostatic pressure up to 1500 MPa.
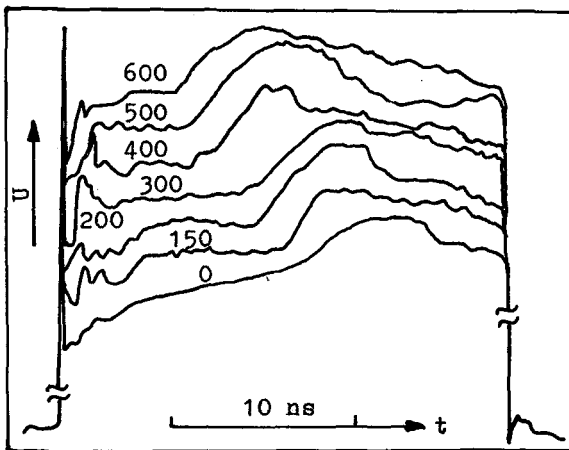

Fig. 2: Potential probe pulses. The average field in the sample is 4.2 kV/cm, the temperature of the measurement 223 K. The distance from the basic probe towards the cathode is noted in micrometers.

4. Hydrostatic pressure measurements.- Application of hydrostatic pressure changes the energy spectrum of electrons in the crystal and the occupation change of particular levels thus leads to an increase or decrease of the threshold field for intervalley transfer of hot electrons. For tellurium however neither the position of the second conduction band nor the pressure dependence of the interband separation are known. Therefore, it was necessary to determine at least the sign of the pressure coefficient from an independent experiment. We have measured the pressure dependence of the anomalous sign reversal in the Hall coefficient /3/.

In tellurium the Hall coefficient shows a twofold sign reversal as the temperature increases: in the transition region from extrinsic to intrinsic conduction and at temperatures above 500 K. The second sign reversal is explained in terms of the thermal occupation of a higher lying low-mobility conduction band at elevated temperatures /2/. We have found in /3/ that the inversion temperature T_i decreases with

increasing hydrostatic pressure. T_i is equal to 475 K and 440 K at 500 MPa and 800 MPa resp.. This means that the interband separation which is proportional to T_i /3/ decreases under hydrostatic pressure. One can anticipate therefore a decrease of the threshold field for n.d.r. if the latter is caused by interband transfer of electrons.

The experimental data presented in fig. 3 support this suggestion. As can be seen from fig. 3, the threshold field decreases under hydrostatic pressure. At pressures exceeding 1000 MPa the current increases at fields below the n.d.r. threshold due to impact ionization. If this ionization is caused by electrons, one can estimate the interband separation at pressures where the ionization onset overtakes the n.d.r. threshold. The interband separation E_{12} at this
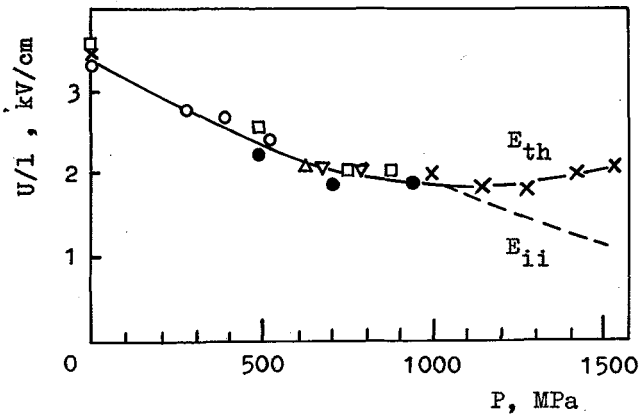

Fig. 3: Pressure dependences of the threshold fields for n.d.r. and impact ionization. The temperature of the measurement was 213 to 233 K.

pressure must be equal to or greater than the ionization energy for an electron $E_i = E_g(2m_e + m_h)/(m_e + m_h)$. The energy gap E_g of tellurium at 1000 MPa is equal to 0.175 eV /4/, which gives a value of 0.21 eV for E_i and also for the minimum interband separation at this pressure. The pressure dependence of E_g in tellurium is exponential /4/ due to the strong nonlinearity of compressibility; therefore, one can anticipate that the dependence of E_{12} has the same character. The extrapolation of E_{12} to atmospheric pressure with the slope obtained from the Hall-effect analysis /1/ gives a minimum value of E_{12} at atmospheric pressure of 0.26 eV.

Furthermore, because no impact ionization occurs at fields below the n.d.r. threshold, the interband separation at atmospheric pressure must be higher than E_i for electrons. This gives E_{12} = 0.38 eV as the maximum value for the interband separation at atmospheric pressure.

5. Monte Carlo calculations.- We made calculations of velocity-field characteristics and of the low-field electron mobility at various

lattice temperatures including some sets of band structure and scattering parameters. The low-field mobility was found from the calculated low-field diffusion constant. A two-level structure of the conduction band was assumed. An electron mass of 0.06 m_o was used in the lowest H valleys, calculations were performed both with a parabolic model and a two-band nonparabolic Kane model for the H valleys. An analysis of galvanomagnetic effects in intrinsic tellurium shows that the effective mass must be ectremely high in the second conduction band. We have used a value of 10 m_o for m_2 in our calculations. E_{12} = 0.3 eV was chosen. The following scattering mechanisms were taken into account: polar optical as well as optical and acoustical deformation potential interaction with phonons, and scattering by ionized centers with a concentration of 10^{16} cm^{-3}. A comparison was made with the temperature dependence of electron mobility measured in /5/ and with the values of the threshold field for n.d.r.. A preliminary analysis shows that the agreement between measured and calcu-
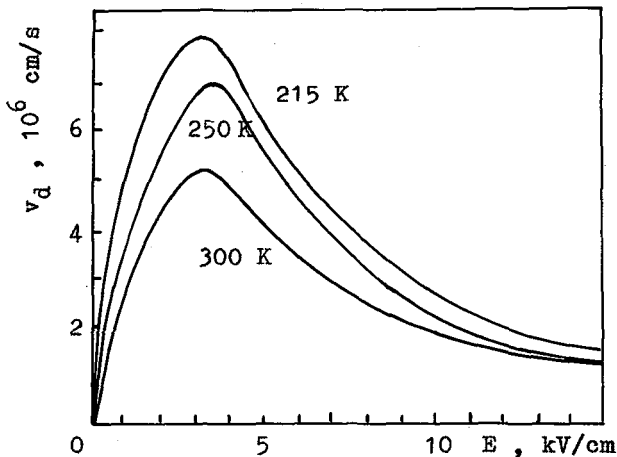

Fig. 4: Calculated field dependences of electron drift velocity at various lattice temperatures.

lated data is the best for the model including only a weak nonparabolicity of the H bands (nonparabolicity constant 2 eV^{-1}) and dominant optical deformation potential scattering with a coupling constant of 10^9 eV/cm. In fig. 4 some velocity-field characteristics are shown calculated on the basis of this model. The calculations show that the electron transfer effect in tellurium is characterized by a rather high peak-to-valley ratio of the drift velocities v_{peak}/v_{valley} = 5 at 215 K.

6. Conclusions.- N.d.r. and moving high field domains in intrinsic tellurium single crystals were observed. Investigations made under

hydrostatic pressure have shown that the n.d.r. is due to electron
transfer into a second conduction ban lying at approximately 0.26 -
0.38 eV above the first one. Monte Carlo calculations predict a high
peak-to-valley ratio suggesting that n-type tellurium would be a
good material for effective Gunn oscillators.

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