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NOTE

Negative resistance of silicon p–n junctions at 4·2°K

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IMPACT ionization of neutral donors at low temperatures has been observed in bulk samples of both germanium(1) and silicon.(2) It has been found that the material is essentially insulating until a critical field for impact ionization is reached, and the material then becomes conducting. In these(1,2) works, the current–voltage characteristics of bulk samples with ohmic contacts were non-linear but no negative resistance regions were observed. This note reports a study of silicon p–n junctions in which the majority carriers in the n-region are created by such impact ionization of donors rather than by thermal or photon excitation. It is found that in the forward direction, the structures studied exhibit a negative-resistance region caused by the injection of minority carriers into the impact-ionization region. IZUMI(3) has reported the observation of negative resistance in the forward-biased direction of alloyed silicon p–n junctions at low temperatures. Additional investigation of p–n junction at low temperatures have been made by MELNGAILIS.(4)

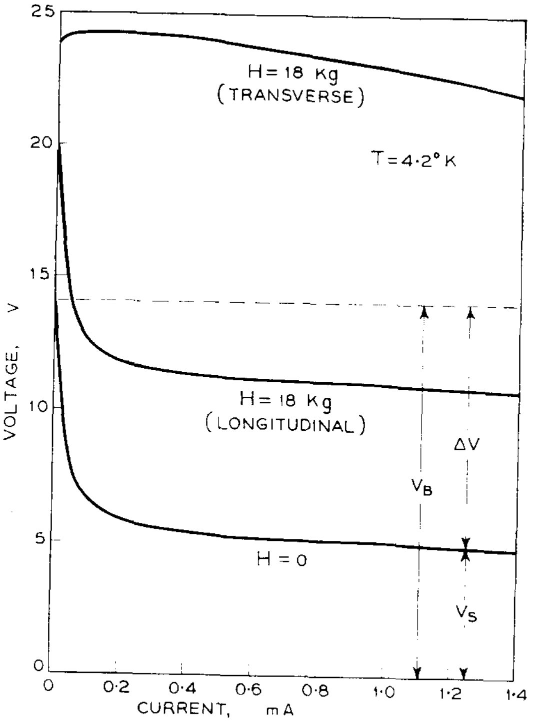

FIG. 1. Forward current–voltage characteristics of a silicon p–n junction at 4·2°K. The breakdown voltage V_B, the sustain voltage V_S, and $\Delta V = V_B - V_S$ are shown for the case of zero magnetic field.

A typical junction of 10^{-6} cm^2 in area was fabricated by diffusing boron a distance of 0·001 in. into a 0·1 Ω-cm n-type silicon wafer 0·010 in. thick resulting in a degenerate p-type surface layer. A degenerate n-type surface layer 0·001 in. thick was diffused into the other side to insure ohmic contact to the n-region. Contacts were made by gold-plating the degenerate end layers. Junctions made by alloying aluminum into silicon did not show any negative-resistance characteristics. It is possible that this behavior is related to the lower doping level produced by aluminum. Measurements of current–voltage characteristics were made on an x–y recorder and also observed on an oscilloscope. The reverse breakdown was 40 V at 300°K and 55 V at 4·2°K. A typical forward current–voltage curve is shown in Fig. 1. We define V_B as the initial breakdown voltage and V_S as the sustain voltage. We also define the quantity $\Delta V = V_B - V_S$. Measurement of the resistance in the high-impedance portion of the I–V characteristic was limited by leakage current in the equipment and found to be greater than 5×10^7 Ω. The forward breakdown occurs in the vicinity of 500 V/cm in the n-region. The conducting region sometimes exhibited a fine structure which varied from sample to sample but the gross characteristics were reproducible.

Measurements in a magnetic field were made to obtain a better understanding of the mechanisms involved. The I–V characteristics in both a longitudinal and transverse magnetic field of 18 kG are shown in Fig. 1. It is seen that, in a longitudinal field, V_B increases while ΔV remains constant. In a transverse field, V_B increased more than in the longitudinal case and ΔV decreases.

No detailed high-frequency characterization of the diode was carried out. However, the diode was made the active element in a relaxation oscillator circuit and operation up to 5 Mc/s was achieved with the upper frequency being limited by the test circuit.

A model by which the results can be explained qualitatively is given schematically in Fig. 2, which shows the band edges for the *n*-region. Before breakdown (a) the donors are neutral and the electric field is uniform across the insulating *n*-region. At the critical field, some donors are impact-ionized (b) and conduction takes place. A similar phenomenon occurs on the *p*-side resulting in the injection of holes into the *n*-region (c). Within a distance L which the holes penetrate into the *n*-region, extra electrons are drawn in to maintain space-charge neutrality. In this region, impact ionization is no longer necessary to maintain conduction and the donors become neutral. This implies that the field in this region is less than the critical field necessary to produce impact ionization and the total voltage across the unit drops. It follows then that the magnitude of the decrease in voltage, ΔV, is determined by the distance L which the holes travel before recombining and it is noted that ΔV increases with increasing current.

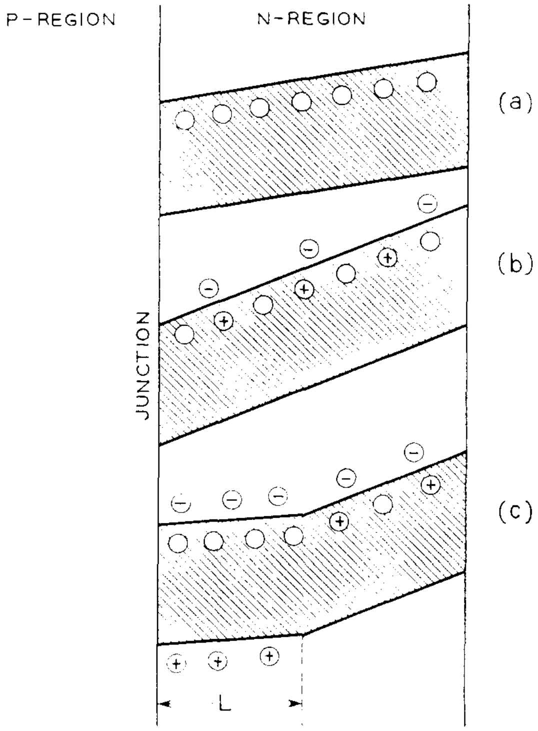

FIG. 2. Schematic diagram of the band edges vs. distance in the *n*-region of a silicon *p–n* junction. (a) Before impact ionization. (b) The onset of impact ionization. (c) The effect of hole injections on the field distribution.

Another diode was constructed in which the *n*-region consisted of an epitaxial layer 10 μ thick on a degenerate *n*-type silicon substrate. In this structure, the *n*-region was thinner than the maximum penetration length of the holes so that the major voltage drop across the structure once conduction started was that of the barrier height at the junction. The forward breakdown voltage was 1·9 V and the voltage dropped to 1·1 V in the conducting region. It was observed in measurements as a function of temperature that the initial breakdown spike was gradually superimposed on the room temperature *I–V* characteristics as the temperature was lowered.

The observed dependence on magnetic field can be attributed to the magnetic dependence of carrier mobilities. In a longitudinal magnetic field, the electrons exhibit an appreciable magneto-resistance while the holes do not. This causes the critical impact ionization field to increase without decreasing the drift length of holes into the *n*-region. In a transverse magnetic field, both carriers exhibit magneto-resistance causing a decrease in hole drift length as well as an increase in breakdown voltage.

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References

1. N. SCLAR, E. BURNSTEIN, W. J. TURNER and J. W. DAVISSON, *Phys. Rev.* **91,** 215 (1953); N. SCLAR and E. BURNSTEIN, *J. Phys. Chem. Solids* **2,** 1 (1957); S. H. KOENIG and G. R. GUENTHER-MOHR, *Ibid.* **2,** 268 (1957).
2. W. KAISER and G. H. WHEATLEY, *Phys. Rev. Letters* **3,** 334 (1959).
3. H. IZUMI, *Proc. I.R.E.* **49,** 1313 (1961).
4. I. MELNGAILIS, *Proc. I.R.E.* **49,** 352 (1961).