phys. stat. sol. (a) 48, 323 (1978)

Subject classification: 14.3.4; 22.1.2

Institute of Physics (a) and Institute of Semiconductors (b), Academy of Sciences of the Ukrainian SSR, Kiev, and Zentralinstitut für Elektronenphysik der Akademie der Wissenschaften der DDR, Berlin (c)

Static High Field Domains in n-Si

By

L. F. KURTENOK (a), E. A. MOVCHAN (a), O. G. SARBEY (a), V. V. MITIN (b), and M. ASCHE (c)

The behaviour of static high field domains in Si is investigated, when there is ndc realized for the ⟨100⟩ crystallographic orientation at temperatures below 50 K. If the parasitic capacities do not influence the measurements there are three groups of samples according to the boundary conditions. In dumb-bell shaped samples where the contact region plays no role at all, the static high field domains are nucleated at the anode independently on the polarity of the voltage applied and in accordance with the theory presented. In samples cut in the form of parallelepipeds the behaviour is explained by a n^{++}–$n^-$$n^+$ structure of the Sb doped Au contacts alloyed to Si, leading to a zone with high field strength always near the cathode if both contacts are equal. If there is an inhomogeneity near one side of the dumb-bell or parallelepiped shaped samples the domain is created always at that end. In each case the region of the static high field domain increases with growing voltage applied until it occupies the whole sample. The mean field strength within the domain amounts to 140 to 200 V/cm varying for different samples and temperatures, but the field strength outside the domain remains at 30 to 45 V/cm.

Исследовано поведение статических доменов сильного поля в n-Si при температуре ниже 50 K, когда в ⟨100⟩ кристаллографическом направлении реализуется ОДС. Если паразитные емкости не искажают измерений, то все образцы можно разделить на три группы. В образцах гантелевидной формы, когда приконтактные области не играют роли, статические домены зарождаются на аноде независимо от полярности напряжения на образце в согласии с теорией. — В образцах в форме параллелипипеда домены зарождаются на катоде, если оба контакта одинаковы. Такое поведение обясняется n^{++}–n^-–n^+ структурой применявшегося Au(Sb) вплавного контакта. — Если в образцах той и другой форм вблизи одного из концов существует неоднородность, то домен зарождается всегда на этом конце независимо от полярности напряжения. — С ростом электрического поля домен расширяется, заполняя все пространство образца. Среднее электрическое поле в домене составляет примерно 140 до 200 V/cm, вне домена 30 до 45 V/cm.

1. Introduction

As shown in [1, 2] for short-time measurements the current–voltage characteristics of n-Si exhibit a range of negative differential conductivity (Fig. 1) for the current directed along ⟨100⟩ and temperatures below 50 K. In the stationary state on the other hand a saturated current behaviour is observed [3, 4], often accompanied by current oscillations [4, 5]. As is well known [6, 7] saturated current behaviour instead of ndc is realized if high field domains are developed in the sample. Some aspects of the behaviour of such domains are represented in this paper.

2. Experimental Arrangements and Results

The current–voltage characteristics and the spatial distribution of the potential were investigated for P-doped Si with resistivities at room temperature between 10 and 100 Ωcm. The samples were cut along ⟨100⟩ either in the form of parallelepipeds

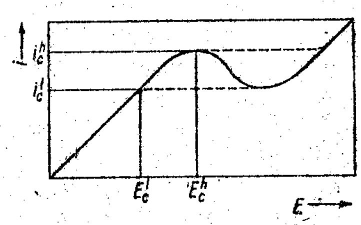


Fig. 1. N-type current–voltage characteristics, the possible saturation currents i_s in dependence on the boundary conditions are shown by dashed lines

or dumb-bells. The mean field strength — up to 200 V/cm — was produced by rectangular voltage pulses of some μs duration and precaution was taken to diminish the parasitic capacities connected with the leads in the cryogenic system. The contacts to the samples were alloyed from Sb-doped Au as usually for investigations of hot electrons in Si. The measurements were performed in the temperature region 27 to 60 K.

Fig. 2 to 4 demonstrate the current–voltage characteristics showing a region of saturated current behaviour typical for temperatures below 45 K as known from [3, 4], while for temperatures above 50 K neither ndc nor saturated current behaviour was observed. In all samples including those with well expressed current oscillations[1]) the measurements of the field distribution exhibited a region of enlargened field strength — a static high field domain.

For not too low temperatures the samples cut in the form of a parallelepiped can be divided into two groups with regard to the localization of the nucleation of the domain. In one group the domains are always created near the cathode and therefore a change of the polarity of the voltage applied is accompanied by a change of the current electrode near which the domain is built up (Fig. 2). These samples will be denoted as cathode–cathode type. In the other group the domain is created at one and the same place near one of the current contacts not depending on the polarity of the voltage applied — cathode–anode type (Fig. 3). Furtheron it should be noticed that the region of the high field domain increases with growing voltage applied. By the way it is to be mentioned that if the domain occupies the whole sample again an almost ohmic behaviour of the current–voltage characteristics is observed. The field

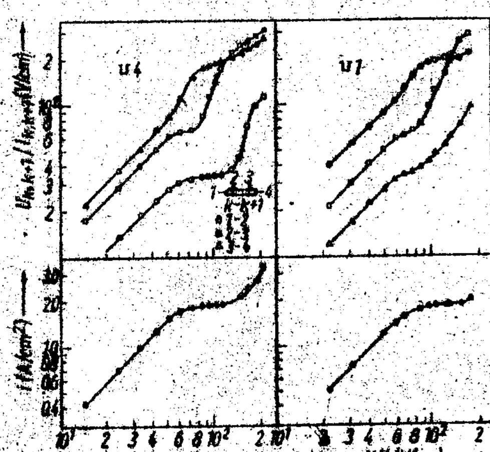


Fig. 2. Current–voltage characteristics (on the lower part) and the distribution of mean field strength of different regions of the sample versus field strength applied for the cathode–cathode type (see text) for $\varrho_{300\,K} = 50\ \Omega$cm, $T = 40$ K

1) Their frequencies in the range of some MHz did not depend on the parameters of the circuit. Their form depends on the voltage applied, however, similar to [8].

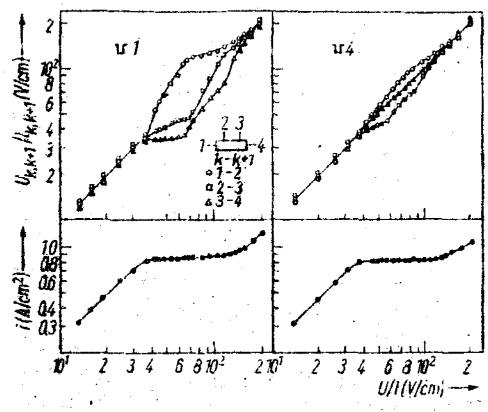


Fig. 3

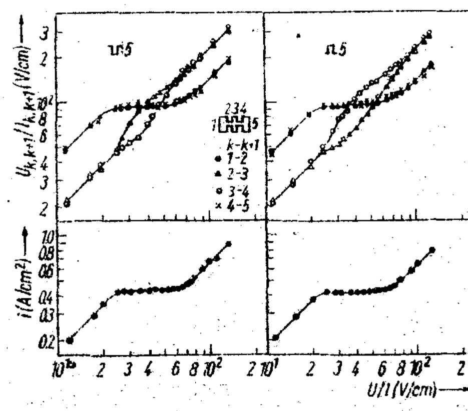


Fig. 4

Fig. 3. Current–voltage characteristics and the distribution of field strength for the cathode–anode type for $\varrho_{300\,K} = 50\ \Omega cm$, $T = 38.5$ K

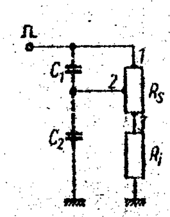
Fig. 4. Current–voltage characteristics and the distribution of field strength for the anode–anode type behaviour of dumb-bell shaped samples for $\varrho_{300\,K} = 50\ \Omega cm$, $T = 34.2$ K. With regard to U_{12}/l_{12} and U_{45}/l_{45} the values of the ordinate have to be diminished 10 times

strength within the static domain amounts of 140 to 200 V/cm varying for different samples and temperatures, but the field strength outside the domain remains at 30 to 45 V/cm.

The dumb-bell shaped samples[2]) can be divided into two groups, too. In the first one — similar to the second group of parallelepipeds — the domain is built up near one of the ends of the slender midsection of the sample not depending on the polarity of the voltage applied — cathode–anode type. For the other group the domain always appears at the positive end of the slender midsection (Fig. 4) in contrast to samples in the form of parallelepipeds. These samples are denoted as anode–anode type. The field strengths inside and outside the domain agree well for differently shaped samples.

At low temperatures (below 30 K) when the resistance of the samples becomes high in contrast to the measurements in the temperature region described above the results are influenced by the not fully (only partially) compensated capacities as a detailed analysis demonstrated. Under this condition the domain always appears at that end of the sample which was connected to the generator independent of the polarity of the pulse. In order to explain this effect in Fig. 5 the capacitances consisting of parasitic and partially compensating contributions are shown schematically. As a matter of fact it has to be taken into account that a precise compensation of the parasitic capacities is not possible because of the nonuniform and time depending

Fig. 5. Simplified equivalent scheme for a measurement of the voltage distribution by an ohmic probe "2". R_s and R_i denoting the resistance of the sample and a resistor for the determination of the current density, respectively. C_1 and C_2 represent the capacities playing the dominating role at low temperatures (27 K)



[2]) The field strength in the massive ends was always smaller than E_c (Fig. 1).

resistances of parts 1 to 2 and 2 to 3, respectively. Therefore during the nonstationary state the voltage drop along 1 to 2 and 2 to 3, respectively, differs from the value under stationary conditions. If the time constant of the circuit $R_{12}(R_{23} + R_i)(C_1 + C_2)/(R_{12} + R_{23} + R_i)$ is longer than the time necessary to build up the domain, the domain appears at the electrode with the larger field strength.[3]) The domain built up favours the inhomogeneous distribution of field strength and consequently no other domain originates in the remaining part of the sample. At low temperature therefore the ratio of C_1 and C_2 determines the electrode at which the domain is built up as could be verified experimentally.

Besides in the region of saturated current behaviour the duration of the current pulse was longer than that of the voltage pulse applied without a noticeable change of the rectangular pulse form. This can be explained by the discharge of C_1 and C_2 leading to a current in the circuit equal to the current through the crystal during the pulse until the voltage drop on the crystal became smaller than the value corresponding to the field strength E_c^l or E_c^h depending on the stationary characteristic realized.

3. Theory and Discussion of the Results

A uniform distribution of the field strength is not stable under the condition of ndc [6, 7], inhomogeneous distributions and current–voltage characteristics connected with them have to be concerned.

As in the samples investigated according to Fig. 2 to 4 the Maxwellian relaxation time is smaller than the intervalley scattering time of electrons, the Poisson equation solved usually is to be replaced by the condition of quasi-neutrality, and the non-uniform distribution is to be obtained by the condition of continuity of the current densities of the various valleys $\boldsymbol{i}_\alpha$. The system of equations to be solved has the following form:

$$\left.\begin{aligned} \frac{1}{e}\operatorname{div}\boldsymbol{i}_\alpha &= \sum_{\beta\neq\alpha}\left(\frac{n_\alpha}{\tau_\alpha}-\frac{n_\beta}{\tau_\beta}\right)+\frac{\partial n_\alpha}{\partial t}, \\ \sum_{\alpha=1}^{\lambda} n_\alpha &= \lambda n_0 . \end{aligned}\right\} \tag{1}$$

τ_α denoting the time of intervalley scattering of electrons of the α-th valley, λ equals the number of valleys regarded, and $n_\alpha = n_0$ for $i = 0$.

It is assumed that the total electron density does not depend on the coordinate with exception of narrow regions near the contacts, which are regarded by the boundary conditions. As the current flows along ⟨100⟩ — chosen as x-coordinate — there are one pair of valleys with small mobility (index 1) and two pairs of valleys with high mobility (index 2). In the y- and z-directions the distribution is homogeneous and stable and the problem is a one-dimensional therefore. As the intervalley scattering times depend on E much stronger than $\mu^{(\alpha)}$ and $D^{(\alpha)}$ do and as the ndc is realized at not too high heating field strengths the diffusion coefficients and mobilities can be represented by their thermal equilibrium values. Therefore, only τ_α and n_α are functions of E and x [9], and the common expression for the current density can be used in the form

$$i_{\alpha x} = eD^{(\alpha)}\left(\frac{\mathrm{d}n_\alpha}{\mathrm{d}x} + n_\alpha \varepsilon_x\right) \tag{2}$$

---

[3]) When the lattice temperature is raised the resistivity of the samples decreases and therefore the time constant of the circuit is diminished and does not influence the appearance of the domain.

with

$$\varepsilon_x = \frac{eE_x}{k_B T}.$$

Because the total current density $i = \sum_{\alpha=1}^{\lambda} i_{\alpha x}$ does not depend on the coordinate, from (1) and (2) an equation for the redistribution of carriers between the two groups of valleys $f = (n_1 - n_2)/(\lambda n_0)$ can be obtained:

$$p \frac{\partial}{\partial f} (pg(f) - \gamma h(f)) - \tau_0 \frac{\partial f}{\partial t} = R(f - \beta), \tag{3}$$

p denoting $\partial f/\partial \eta$ with $\eta = x/L$, $L^2 = (1/\lambda)[D^{(2)} + (\lambda - 1) D^{(1)}] \tau_0$ and $\tau_0 = \tau_\alpha(\varepsilon = 0)$, further $g(f) = (1 - ab)/(1 - bf)$, and $h(f) = (a - f)/(1 - bf)$ with

$$a = \frac{D^{(2)} - D^{(1)}}{D^{(2)} + (\lambda - 1) D^{(1)}} \quad \text{and} \quad b = \frac{D^{(2)} - D^{(1)}}{D^{(2)} + D^{(1)}/(\lambda - 1)},$$

γ denoting $\dfrac{i\tau_0}{e\lambda n_0 L} \dfrac{D^{(2)} + (\lambda - 1) D^{(1)}}{D^{(1)} + (\lambda - 1) D^{(2)}}$, $R = \tau_0 \dfrac{(\lambda - 1) \tau_2 + \tau_1}{\tau_1 \tau_2}$, and $\beta = \dfrac{\tau_1 - \tau_2}{\tau_1 + (\lambda - 1) \tau_2}$.

Equation (3) was analyzed in the p, f phase plane and because of $\gamma \gg 1$ the solution is presented in the form of domains and domain walls [9]. When $i_0^l \leqq i \leqq i_c^h$ the equation of the uniform problem

$$f = \beta$$

has three solutions f_i with $f_1 \leqq f_2 \leqq f_3$. The phase trajectories are determined by the boundary conditions on the surfaces $x = \pm l$, which are given by equations of the type $p^+ = p^+(f^+)$, and $p^- = p^-(f^-)$, respectively. The crossing points of these curves and the phase trajectories determine the values of f^+ and f^- at the surfaces $x = \pm l$, i.e. those of the trajectories which begin at $f = f^-$ and end at $f = f^+$. In this way the analysis is performed taking f^- and f^+ as given values in the region of the contacts.

If the redistribution of carriers f^+ at the cathode ($x = +l$) is smaller than f_1 for all values $i_c^l \leqq i \leqq i_c^h$ the domain is originated at the anode and the saturation current i_s approximates i_c^h. This case is realized for non-rectifying contacts. If the redistribution of carriers at the cathode is bigger than f_3 the domain is built up at the cathode and i approximates i_c^l. Such a situation is realized for rectifying contacts. However, if $f_1 \leqq f^+ \leqq f_3$ the situation is more complicated. For fixed voltage static domains cannot be realized [9]. Analyzing the time-dependent equations a stationarily moving domain is obtained as a solution, leading to current oscillations.

Comparing these results and the experimental data it is easy to see that the nucleation of static domains at the anode of the dumb-bell shaped samples agrees with the theory as there are no doubts about the surface conditions applied on the theoretical side and realized in the experiments.

In order to explain the data for the nucleation of the domain near the cathode (Fig. 2) qualitatively it is necessary to discuss the structure of the contacts alloyed to Si by Sb-doped Au. Comparing the diffusion coefficients of Au and Sb in Si ($D_{Au} \approx \approx 3.4 \times 10^{-9}$ cm²/s and $D_{Sb} \approx 2 \times 10^{-19}$ cm²/s [10]) and their solubilities at the alloying temperature of about 700 °C ($S_{Au} = 7 \times 10^{14}$ cm⁻³ and S_{Sb} being 3 to 4 orders of magnitude higher) it can be estimated that the contacts have a n^{++}–n–n^+ structure, n^{++} denoting the degenerated region on account of Sb, n denoting a high resistivity region obtained by compensation of Sb and P by Au-diffusion, and n^+ characterizing the doping of the volume of the sample. Under these assumptions, if the parameters n at both contacts are almost the same the domain is nucleated at the cathode for both polarities of the voltage applied. If the values for n differ at both contacts the domain is created in that n-region with the higher resistivity and changes from cathode to anode when the polarity is altered in dependence on the difference of the Au concentration on both ends of the sample.

By the way the distribution of the field strength in the ohmic region is not always strictly the same when the polarity is changed, i.e. the curves U_{12}/l_{12} and U_{34}/l_{34} are interchanged (Fig. 2). This fact demonstrates a small voltage drop near the cathode showing the assumption of a n^{++}–n–n^{+} type contact to be realistic. It is to be mentioned that such a type of contact was regarded in [11].

A more detailed comparison of theoretical and experimental data is difficult because of the micro-inhomogeneity of the crystal, demonstrated by the high percentage of samples in which the domain is built up at one and the same end of the sample independent of polarity and by the circumstance that the growth of the domains with increasing field strength does not coincide quantitatively for both polarities (Fig. 2 to 4). Besides, because of the small differences between i_c^h and i_c^l in n-Si in the region of temperatures investigated it is impossible to decide to which of these values i_s corresponds.

References

[1] N. O. Gram, Phys. Letters A 38, 235 (1972).
[2] C. Canali, C. Jacoboni, F. Nava, G. Ottaviani, and A. Alberigi-Quaranta, Phys. Rev. B 12, 2265 (1975).
[3] M. Asche and O. G. Sarbei, phys. stat. sol. (b) 46, K121 (1971).
[4] M. H. Jørgensen, N. O. Gram, and N. I. Meyer, Solid State Commun. 10, 337 (1972).
[5] M. Asche and O. G. Sarbei, phys. stat. sol. (a) 8, K61 (1971).
[6] W. L. Bonch-Bruevich, I. P. Zvyagin, and A. G. Mironov, Domennaya eletricheskaya neustoichivostv poluprovodnikakh, Izd. Nauka, 1972.
[7] A. F. Volkov and Sh. M. Kogan, Uspekhi fiz. Nauk 96, 633 (1968).
[8] M. Asche and E. Russu, phys. stat. sol. (b) 66, 499 (1974).
[9] V. V. Mitin, Fiz. Tekh. Poluprov. 11, 1233 (1977).
[10] B. J. Boltaks, Diffusiya i tochechnye defekti v poluprovodnikakh, Izd. Nauka, 1972.
[11] M. Lampert and P. Mark, Inektsionnie toki v tverdikh telakh, Mir, 1973 (p. 218).

(Received March 7, 1978)