Dynamic current-voltage characteristics of photosensitive layer structures based on heavily doped Si:As with blocked impurity-band conduction

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The approximation of Schottky depletion layers is used in calculation of the transient characteristics of a current flowing through a semiconductor photosensitive structure with blocked impurity-band conduction. Calculations are carried out for an arbitrary law describing the time dependence of the applied voltage $V(t)$. It is shown that dynamic current-voltage characteristics of such structures subjected to triangular voltage pulses $V(t)=\beta t$ ($\beta=\text{const}\gtrless 0$) can be used to determine the main physical parameters of a structure (which are the thicknesses of the active and blocking layers, the concentration of the compensating impurity in the active layer, and the impurity band conductivity) and also to identify the presence of an excess electric charge in the blocking layer. A report is given of an experimental investigation of dynamic current-voltage characteristics ($\beta=\pm 10^{-2}$ V/s) of n-type Si:As structures with blocked impurity-band conduction at liquid-helium temperatures, $T\leqslant 10$ K. In the range $T\gtrsim 6$ K, these current-voltage characteristics are in the quasisteady-state. They are in agreement with the results of calculations and are governed primarily by the process of modification of the space charge region depleted of positively charged donors. At temperatures $T\lesssim 6$ K, the space charge region forms under highly transient conditions. In this case it was found that the field effects played a considerable role: they destroyed correlations in the spatial distribution of ionized donors and acceptors, and increased the electrical conductivity σ. An allowance for the field dependence of σ made it possible to describe satisfactorily the experimental dynamic current-voltage characteristic at temperatures $T\lesssim 6$ K.

The impurity photoconductivity of silicon structures with blocked impurity-band conduction is currently attracting considerable attention.[1-4] Structures exhibiting such photoconductivity are usually prepared by the methods of vapor or molecular-beam epitaxy. An active layer of lightly doped, compensated silicon 10-20 μm thick is grown first on a degenerate substrate, followed by growing a thin blocking layer of undoped silicon, several microns thick, on which an ohmic contact is deposited. The impurity concentration in an active layer is $\sim 10^{17}$-10^{18} cm^{-3}, which represents $\sim 10\%$ of the critical concentration corresponding to the Mott transition.[5] Heavy doping of the active layer ensures a high quantum efficiency, in spite of the low dimensions of the extrinsic photodetector, but in the temperature range of impurity freezeout the conductivity of the active layer responsible for the dark current may be considerable because of the hopping of carriers inside an impurity energy band. Introduction of a blocking layer increases the dark resistance of a structure and ensures a considerable reduction of this resistance under photoexcitation conditions. However, in the case of structures with blocked impurity-band conduction there are not only problems typical of extrinsic photodetectors based on bulk silicon (the main problem is the control of the degree of compensation of the dopant[1]), but also major problems of control of the structure parameters and particularly those of the active layer,[1] as well as problems encountered in the study of the transport processes in an impurity energy band, because these processes govern the response time of a photodetector.

We shall show that an analysis of dynamic current-voltage characteristics of structures with blocked impurity-band conduction can provide the information needed to successfully solve these problems.

We shall now consider the energy band diagram of a structure of this kind in an external electric field and we shall assume specifically that we are dealing with n-type Si (Fig. 1). The potential V applied to the contact with the blocking layer is positive relative to the potential applied into the rear contact (substrate) with the heavily doped active layer, which corresponds to the operating conditions in the case of a photodetector with blocked impurity-band conduction. In the space charge region (II in Fig. 1) the donors are largely neutralized. In other words, the space charge region is depleted of positively charged donors because of hopping transport of carriers in the active layer between the impurity band states (this involves electron jumps from neutral donors to vacant $N_D{}^+$ sites, due to the presence of compensating acceptor impurities which we shall call the A^- centers). We assume that donors partly compensated by acceptors may be present in relatively small concentrations ($\lesssim 10^{14}$ cm^{-3}) in the blocking layer of undoped silicon; in Fig. 1 this is symbolized by the discrete plus and minus signs. Therefore, at the boundary between the active and blocking layers there is in fact no potential barrier that would hinder the motion of free electrons from the space charge region II to a region labeled I, so that accumulation of these electrons at the boundary in question (i.e., accumulation in the surface layer of the semiconductor) is impossible. We also assume that the temperature is sufficiently low to justify disregard of the thermal field and impact ionization of donors, and also the conductivity of the blocking layer in electric fields $\sim 10^3$ V/cm, which are typical of the operation of structures with blocked impurity-band conduction.

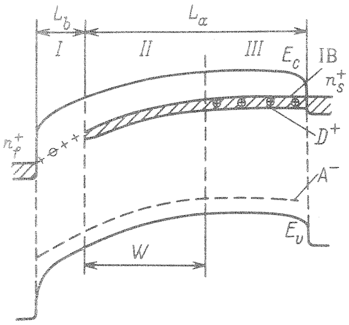

FIG. 1. Energy band diagram of a structure with blocked impurity-band conduction, subjected to a positive bias applied to the front contact: I) blocking layer of undoped silicon; II, III) active layer; II) space charge region; n_f^+ is the front contact and n_s^+ is the rear contact; D^+ represents positively charged donors or vacancies; A^- are negatively charged acceptors; IB is the impurity band; E_c is the bottom of the conduction band and E_v is the top of the valence band of silicon; W is the thickness of the space charge region.

We shall consider the kinetics of the current flowing through a structure when the voltage V applied to it is varied. Let us assume that at some time t the voltage $V(t)$ creates in the active layer a region of width $W(t)$ depleted of positively charged donors. Solving the Poisson equation in the approximation of Schottky depletion layers,[2)] we find the relationship between $W(t)$, the electric field in the blocking layer $E_b(t)$, the field in the electrically neutral part of the active layer $E_a(t)$, and the external voltage $V(t)$:

$$E_b(t) = E_a(t) + \frac{4\pi q}{\varkappa} N_A W(t), \tag{1}$$

$$W(t) = -L_b + \left\{L_b^2 + \frac{\varkappa}{2\pi q N_A}\left[V(t) - E_a(t)(L_a + L_b)\right]\right\}^{1/2}, \tag{2}$$

where q is the elementary charge, $\varkappa$ is the permittivity of the semiconductor, and L_a and L_b are the thicknesses of the active and blocking layers, respectively. It follows from the condition of continuity of the total current

$$I = \text{const} = \frac{\varkappa}{4\pi}\frac{dE_b}{dt} = \left(\sigma E_a + \frac{\varkappa}{4\pi}\frac{dE_a}{dt}\right) S$$

and from Eqs. (1) and (2) that the current can be described by

$$I(t) = \frac{\varkappa S}{4\pi (L_a + L_b)}\left\{\frac{dV}{dt} + E_a(t)\frac{4\pi\sigma}{\varkappa}\left[L_a - W(t)\right]\right\}, \tag{3}$$

and the equation for the electric field in the electrically neutral part of the active layer is

$$\frac{dE_a}{dt} + \frac{4\pi\sigma (W(t) + L_b) E_a(t)}{\varkappa (L_a + L_b)} - \frac{1}{L_a + L_b}\frac{dV}{dt} = 0. \tag{4}$$

Here S is the area of the structure, and σ is the impurity-band conductivity which generally depends on the electric field E_a (Ref. 5).

Equations (3) and (4) and the expression (2) can be used, if the profile of the signal $V(t)$ is known, to determine – in principle – the parameters of a structure with a blocked impurity-band conduction of interest to us from the experimentally determined transient current characteristic $I(t)$. In particular, if the voltage is varied linearly, $V = \beta t$ (β = const), then in the simplest case, where the observation time obeys $t \gtrsim \varepsilon(L_a + L_b)/4\pi\sigma L_b$, the process of formation of the space charge region is quasisteady [the first term in Eq. (4) is unimportant] and we have

$$I(t) = \frac{\varkappa\beta S}{4\pi\left[W(t) + L_b\right]}, \tag{5}$$

where

$$W(t) = -L_b + \left\{L_b^2 + \frac{\varkappa\beta}{2\pi q N_A} t\right\}^{1/2}.$$

Since $I(t)$ is simply the capacitative current flowing through a structure with blocked impurity-band conduction, we find that if the dependence $I(t) \equiv I(V/\beta)$ is represented using the Schottky coordinates I^{-2} and V, we should have a straight line whose slope should give N_A, i.e., the concentration of the compensating impurity in the active layer. Obviously, at low values of V the dependence of I^{-2} on V flattens, because for $V < 0$ a region rich in N_D^+ vacancies forms inside the active layer and the width of this region is considerably less than L_b because of the high dopant concentration in the active layer. The current I then ceases to depend on time and its value is governed by the thickness of the blocking layer L_b: $I = \varkappa\beta S/4\pi L_b$.

It is interesting to consider also the transient case, in particular, the response of a structure for observation times $t \propto \varkappa(L_a + L_b)/4\pi\sigma L_b$. It follows from Eqs. (3) and (4) that under these conditions the $I(t)$ curve is largely determined by the impurity-band conductivity and the change in the current, ΔI, due to reversal of the sign of β represents the quantity $L_a + L_b = \varkappa|\beta|S/2\pi\Delta I$ [see Eq. (3)].

We shall now analyze experimental dynamic current-voltage characteristics of structures with blocked impurity-band conduction and with an active layer made from Si doped with As in a concentration of 7×10^{17} cm^{-3}. The area of the structure was 7.85×10^{-3} cm^2. In the temperature range 4.2-10 K, the structure was subjected to sawtooth-shaped voltage signals V rising at a rate of $\beta \sim \pm 10^{-2}$ V/s and the transient current $I(t) \equiv I(V)$ was recorded. The current and

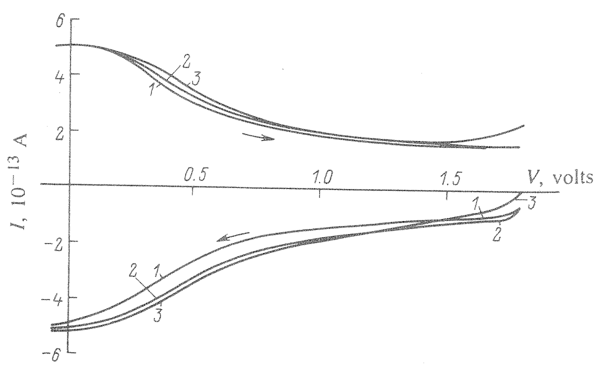

FIG. 2. Dynamic current-voltage characteristics of a structure with blocked impurity-band conduction in the subrange of "high" temperature $T \gtrsim 6$ K in the case where $\beta = \pm 2.4 \times 10^{-2}$ V/s. T (K): 1) 6; 2) 8; 3) 10. The arrows show direction of changes in the voltage V.

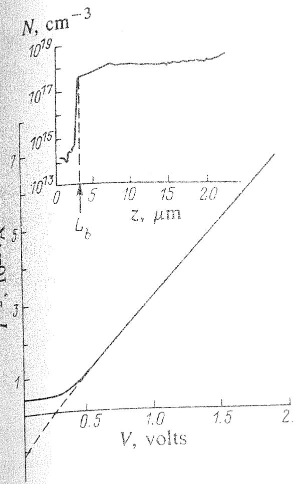

FIG. 3. Dependence of I^{-2} on V plotted using the data of Fig. 2 for 8 K. The inset shows the distribution of the internal impurity in the investigated structure.

the voltage were measured using Shch-300 digital voltmeters; in measurements of the current the signal received by the voltmeter came from a current–voltage converter based on a 544 UD1 operational amplifier with a high input resistance. The control of the experimental procedures, as well as acquisition and processing of the data were carried out by an Élektronika BK 0011 personal computer; the *I-V* characteristic consisted of about 200 experimental points and the signal-to-noise ratio was improved by averaging the results of ten measurements at each value of the current.

The nature of the measured $I[V(t)]$ curves enabled us to divide the investigated temperature range into two subranges: "high-temperature" ($T \gtrsim 6$ K) and low-temperature ($T \lesssim 6$ K). Typical *I-V* characteristics obtained for the first subrange are shown in Fig. 2: they demonstrate that the changes in temperature have little effect on the *I-V* characteristics, and that there is no significant hysteresis when the sign of β is reversed [this can be judged on the basis of the isothermal curves obtained for $\beta > 0$ (at the top of the figure) and $\beta < 0$ (at the bottom)]. Consequently, we conclude that at these temperatures the conductivity σ is quite high and that the quasi-steady regime of formation of the space charge region is realized. The I^{-2} vs V curve should then be a straight line which flattens at low values of V, whose slope is governed by N_A [see Eq. (5) and the adjoining text]. This curve is plotted in Fig. 3. We see that it is in very good agreement with these predictions. The values of N_A and of the thickness of the blocking layer L_b found from this dependence are 8.3×10^{12} cm^{-3} and 3.8 μm, respectively. Direct determination of the distribution of the dopant in the investigated structure with blocked impurity-band conduction, carried out in the course of layer-by-layer etching in an electrolytic cell using the method of capacitance-voltage characteristics (inset in Fig. 3), gives the estimate $L_b \approx 3.3$ μm (corresponding to the onset of a steep fall of the dependence log N_d on z), in satisfactory agreement with the value 3.8 μm given above. This provides further support of the conclusion that at $T \gtrsim 6$ K the space charge region forms under quasisteady conditions.

Extrapolation of the linear part of the curve of I^{-2} vs V so that it intersects the ordinate shows that in the range $V <$

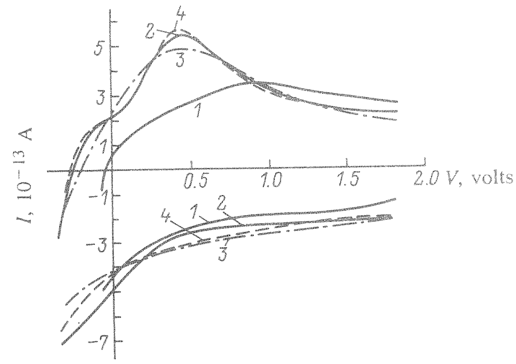

FIG. 4. Dynamic current-voltage characteristics of a structure with blocked impurity-band conduction obtained in the subrange of low temperatures $T \lesssim 6$ K when $\beta = \pm 4.4 \times 10^{-2}$ V/s. T (K): 1) 4.2; 2) 5; 3) the *I-V* characteristic calculated from Eqs. (3) and (4) at 5 K; 4) the *I-V* characteristic calculated from Eqs. (3) and (4) allowing for Eq. (6) at 5 K.

0.25 V (particularly at $V = 0$) we obtained $I^{-2} < 0$. This is clearly seen to be in conflict with Eq. (5). However, the conflict could be avoided by assuming that the blocking layer is not electrically neutral, i.e., that it carries an excess negative charge Q_f due to partial neutralization of the ionized donor impurity by injection from the active layer. Assuming that the distribution of Q_f across the blocking layer thickness is uniform, we find from the Schottky approximation that

$$W(V) = -L_b + [L_b^2 (1 + Q_f/qN_A) + \varkappa V/2\pi qN_A]^{1/2}.$$

Consequently, allowing for the presence of the excess charge in the blocking layer, we conclude that the value at the point of intersection with the ordinate at $V = 0$ is

$$I^{-2}|_{V=0} = (4\pi/\varkappa S\beta)^2 \times L_b^2 (1 + Q_f/qN_A);$$

for $Q_f < 0$, obviously $I^{-2}|_{V=0}$ could be <0. Substituting the value of $I^{-2}|_{V=0}$ in the above expression as well as the values $L_b = 3.8$ μm and $N_A = 8.3 \times 10^{12}$ cm^{-3} found above, we find that $Q_f/q \approx 3 \times 10^{13}$ cm^{-3}. This result is in reasonable agreement with the postulated concentration of the ionized donors in the blocking layer: $Q_f/q < N_D$ ($N_D \approx 10^{14}$ cm^{-3}, see the inset in Fig. 3).

It should be noted that beginning at $T \gtrsim 10$ K at voltages $V \gtrsim 1.5$ V (i.e., when the test structure is in a moderate electric field $E > 10^3$ V/cm was) the current increases with the voltage (Fig. 2); as pointed out already, this could be due to the thermal–field and impact processes of donor ionization[3)] and/or an increase in the conductivity of the blocking layer.

At temperatures $T < 6$ K, the nature of the *I-V* characteristic changes radically. A hysteresis of the corresponding to the rise and fall of the voltage clearly demonstrates that the processes occurring in the structure when the voltage is varied are transient (Fig. 4). In this case the change in the current ΔI due to reversal of the sign of β could be used to find $L_a + L_b = \varkappa|\beta|/2\pi\Delta I \simeq 18$ μm [see also Eq. (3)]. This value is close to the results obtained by direct determination of the distribution profile of the donor impurity, which gave $L_a + L_b = 22$ μm (the inset in Fig. 3). The transient case is described by Eqs. (3) and (4). The impurity-band conductivity σ in these equations determines the Maxwellian relaxation time $\tau_M = \varkappa/4\pi\sigma$, which can easily be found by fitting the *I-V* curve, calculated from Eqs. (3) and (4), to the experimental results, using the values of $L_a + L_b$, L_b and N_a found earlier. The calculated *I-V* curve describes best the experimental results if we assume that $\tau_M \approx 3$ s and $\sigma = \text{const} = 3.5 \times 10^{-13}$ S/cm (curve 3 in Fig. 4; $T = 5$ K); a maximum of the dependence $I[V(t)]$ corresponds to an observation time $t \approx \tau_M(L_a + L_b)/L_b$ (see above), beginning from which we can expect a gradual transition to quasi-steady formation of the space charge region. However, these curves differ considerably: the current maximum of the experimental curve obtained for $\beta > 0$ is preceded by an inflection point. This may be a consequence of an increase in σ of the electrically neutral part of a structure with blocks impurity-band conduction subjected to the electric fields E_a used in the experiments. We can allow for this circumstance by assuming that σ follows instantaneously the changes in E_a. We can then calculate the *I-V* characteristic using Eqs. (3) and (4). The dependence $\sigma(E)$ was calculated in Ref. 6:

$$\sigma(E_a) \approx \sigma_0 \exp\left[\alpha \sqrt{\frac{4q^3 E_a}{\varkappa (kT)^2}}\right], \tag{6}$$

where σ_0 is the impurity-band conductivity in the limit of a weak electric field, k is the Boltzmann constant; and $\alpha = 0.69$ is a constant.[4)] The *I-V* curve calculated from Eqs. (3), (4), and (6) using two fitting parameters $\tau_M{}^0 = \varkappa/4\pi\sigma_0$ and α is also shown in Fig. 4 (curve 4). It is obvious that the agreement between the experimental and calculated curves is good for both $\beta > 0$ and $\beta < 0$ if we assume that $\tau_M{}^0 = 35$ s ($\sigma_0 = 3 \times 10^{-14}$ S/cm) and $\alpha = 0.35$. Therefore, the inflection point exhibited by the experimental *I-V* characteristic should be regarded as the point of transition from the regime of relaxation of the current characterized by $\sigma = \sigma_0 = \text{const}$ to the regime in which σ rises with the observation time. Therefore, the model of rise of σ in an electric field, based on the field-induced destruction of correlations (*I* complexes) in the spatial distribution of ionized donors and acceptors,[6] is capable of describing the experimental dynamic current-voltage characteristics of structures with blocked impurity-band conduction at temperatures $T < 6$ K.

1) We have in mind here a region of complete neutralization of the dopant, which is the main reason for the photosensitivity of such a detector.

2) Introduction of the concept of a Schottky depletion layer is justified by the fact that in the case under consideration the impurity band is essentially an analog of the valence band in which the role of holes is played by the vacant $N_D{}^+$ sites, which appear because of the presence of a compensating acceptor impurity (Fig. 1).

3) It is interesting to note that an estimate based on Eq. (3) gives a critical temperature of 13.5 K for the appearance of such effects. This is the upper limit of the operating temperature of a photodetector, a structure with blocked impurity-band conduction made of Si:As.

4) The experimental values of α given in Ref. 6 are 2-3 times lower than those found by calculation.

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