Carrier accumulation and strong electrode sheath fields in illuminated, high-resistivity MISIM structures

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The influence of the tunnel transmissivity $T_{n,p}$ of an insulation layer on the electric field distribution and the current–intensity $j–I_i$ relation in a purely, highly biased, high-resistivity metal–insulator–semiconductor–metal (MISIM) structure is investigated theoretically. It is shown that as $T_{n,p}$ decreases, carriers accumulate near the oppositely polarized electrodes, and their density rises sharply in layers having a thickness of the order of $l_k = kT/eE_e (E_e = V/d)$. The domain of parameters is determined. In this domain the accumulation effects are so strong as to increase the near-electrode fields appreciably, to the extent that they significantly exceed the mean field. The dependence of the current on the transmissivity is determined by the height of the Schottky barrier. In moderate fields, if the photocurrent is much higher than the dark current, the current density increases slightly with decreasing $T_{n,p}$, tending to the maximum value $eI_i$. In strong fields the current rises sharply as a result of carrier injection across the lowered potential barrier. © 1997 American Institute of Physics.

INTRODUCTION

In metal–semiconductor–metal (MSM) structures the rates of carrier exchange across the boundaries of the semiconductor is of the order of the thermal exchange rates and is much greater than the carrier drift velocities in fields of the order of $10^7$ V/cm. Consequently, carriers do not accumulate in the electrode sheets, and in pure crystals illuminated at moderate intensities the electric field does not undergo sudden changes at the interfaces. The specific characteristics of the photoelectric effect in highly biased, high-resistivity MSM structures under various experimental conditions (i.e., various illumination intensities and applied voltages) and for various bulk parameters of the semiconductor (deep-level impurity concentration and impurity energy level) have been investigated in several papers.1–5 The inclusion of insulating layers between the semiconductor and the metal imparts new significance to several surface parameters such as the barrier height $\varphi_{Bn}$ between the semiconductor and the metal and the tunnel transmissivity $T_{n,p}$ of the insulator film. The influence of $\varphi_{Bn}$ on the field distribution in the cathode zone of the illuminated structure at maximum carrier exchange rates has been studied previously.6 For high-resistivity structures containing a deep-level impurity it has been shown7 that to vary $\varphi_{Bn}$ and $T_{n,p}$ by varying the filling factor of the deep impurity level significantly influences the dark field distribution in the interior (decompensation effect associated with thickening of the insulator film).

The discovery that tunnel transmission influences the dark field distributions in the interior volume makes it necessary to extend research to the case of illumination. The photoelectric effect in metal–insulator–semiconductor–insulator–metal (MISIM) structures with a tunnel-transmissive insulator have been studied previously in Ref. 8 and in several other papers.9 However, these studies addressed conventionally doped, low-resistivity semiconductors with low biases of the order of 1–2 V. The distribution of the electric field in such structures is determined mainly by the doping and changes little under illumination.

The object of the present study is the influence of the tunnel transmissivity of the insulating layer between the semiconductor and metal on the electric field distribution in a highly biased, high-resistivity MISIM structure and the independence of the current and the illumination intensity. To isolate transmissivity effects, we consider a semiconductor without deep-level impurities, so that the volume recombination and charge exchange of traps are excluded from the model. Our investigation is therefore a generalization of Ref. 1 to the case of arbitrary boundary transmissivities.

1. STATEMENT OF THE PROBLEM

We consider an MISIM structure, to which we apply a voltage $V$ much higher than all barriers. Natural monochromatic light ($h \nu \approx E_p$) is incident on the semitransparent anode. Carrier transport in the semiconductor is analyzed on the basis of the system of equations of continuity in the diffusion-drift approximation and the Poisson equation.1 The insulating layers are characterized by the transmissivities $T_n$ and $T_p$ (carrier tunneling probabilities), so that the boundary conditions at the semiconductor–insulator interfaces $x=0$ and $x=d$ have the form (see, e.g., Refs. 1, 9, and 10)

$$q_{n}(0) = -V_{n0}^r\left[n_0 - n_0^e q_{n} \exp\left(-\frac{eV_{0}^n}{kT}\right)\right] - q_{i}(0),$$

$$q_{p}(0) = -V_{p0}^r\left[p_0 - p_0^e q_{p} \exp\left(\frac{eV_{0}^p}{kT}\right)\right] - q_{i}(0),$$

(1)
The graph of $E_\tilde{\eta}$ at the boundaries is written for the model of a single surface $\tilde{X}$. Consequently, the boundary fluxes $10\%$ if the layer thickness is bounded by the values $25–250$ Å. Consequently, the boundary fluxes $(1)$ practically coincide with the expressions discussed in Ref. $1$. (additional allowance is made for surface recombination), but the emission rates $V_n^T$ and $V_p^T$ can vary over wide ranges, since they are proportional to the transmissivities of the insulating layers.

The tunnel transmissivities $T_n$ and $T_p$ depend exponentially on a function that contains the layer thickness $\delta$, the tunneling mass $m_{n,p}$, the barrier height for tunneling $\Phi_{n,p}$, and the voltage drop across the layer $V_i$ (see, e.g., Refs. $9$, $11$, and $12$). In lieu of reliable information on these quantities, we ignore the details of the dependence of $T_n$ and $T_p$ on the film characteristics and use the transmissivity as an input parameter independent of $V_i$.

2. DARK CURRENT

2.1. We investigate a high-resistivity structure of width $d=0.3$ cm with an effective density of acceptors per unit volume $N_a=10^8$ cm$^{-3}$. The height of the barrier between the semiconductor and the metal is taken to be $\varphi_{\eta B} =1$ V. This corresponds to the case in which the equilibrium hole density $p^e$ at the semiconductor boundaries is much higher than $N_u, n_1$, and $n^e$. The voltage applied to the structure is varied between $1$ V and $6000$ V. All other parameters have the same values as in Ref. $1$. The transmissivities are varied in the range $T_n = T_p = 1 - 10^{-5}$.

Figure $1$ shows the electric field distributions $\tilde{E}(X)$ ($\tilde{E}=E/E_e$, $E_e=V/d$, $X=x/d$) at various transmissivities. The graph of $\tilde{E}(X)$ is almost linear and, as the transmissivity decreases, tends to a near-uniform distribution $[\tilde{E}(X) \approx 1]$ with a small negative slope. The density of holes in the interior decreases in this case, and their distribution becomes almost uniform (Fig. $2$). Holes accumulate in a narrow boundary layer of thickness $\delta^* = 10^4 d$ near the cathode, and the density $p_d$ increases, tending to the value $2p_0^e$. The behavior of the electrons is analogous to the hole behavior to within polarity. The density of electrons in the interior is much lower than the hole density and decays therein as the transmissivity decreases. The distribution $n(X)$ makes a sudden jump in the diffusion layer near the anode, tending to the value $2n_0^e$ as the transmissivity decreases. The current–voltage $(I–V)$ characteristic for various values of the transmissivity is shown in Fig. $3$. In the transmissivity range $1 – 10^{-2}$ the current decreases relatively little, but with a further reduction in the transmissivity the $j(T)$ graph becomes more pronounced in the high-voltage range, of the order of several hundred volts. At high voltages the current tends to an asymptotic value, which depends on the transmissivity, reaching the asymptote at lower voltages as the transmissivity decreases.

2.2. The hole distribution $P(X)$ and the electric field distribution $\tilde{E}(X)$ in the dark case have been analyzed theoretically in Ref. $7$ [see Eqs. $(2)$, $(4)$, $(5)$, and $(15)$ therein], where it is shown that the expressions derived in Ref. $1$ for the boundary values of the carrier densities are also valid for arbitrary transmissivity. The graphs of $E(X)$, $P(X)$, and $j(T)$ obtained under the condition $p^e d > N_a$ (Figs. $1$–$3$) are explained by a decrease in the hole fluxes from the metal and the space charge in the interior. A decrease in the transmissivity of the insulating layer causes carriers to accumulate around the electrodes of opposite polarity. It is also the prin...

FIG. 1. Influence of the tunnel transmissivity of the boundaries on the dark electric field profiles, $\tilde{E}=E/E_e$, $E_e=V/d$. $1$) $T=1$; $2$) $10^{-1}$; $3$) $10^{-2}$; $4$) $10^{-3}$; $5$) $10^{-5}$.

FIG. 2. Influence of tunnel transmissivity of the boundaries on the dark hole profiles, $P=p/N_a$. $1$) $T=1$; $2$) $10^{-1}$; $3$) $10^{-2}$; $4$) $10^{-3}$.