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PRELIMINARY INVESTIGATION OF Ag/n–Si(111) SCHOTTKY PHOTODIODE PREPARED BY IONIZED–CLUSTER–BEAM DEPOSITION

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Photocharacteristics in the visible region of Ag/n-Si(111) Schottky photodiode, prepared by ionized–cluster–beam deposition for Ag^+ acceleration voltage equal to zero, have been measured. High quantum efficiency (up to 85%) and responsitivity of 0.35 A/W, when operating in the reversed bias regime, was observed. For low reverse voltages $V_r < 1$ V, the photocurrent measurements exhibit strong, unusual voltage dependence of the depletion layer width. The $I - V$ data in this regime could be well fitted by an expression proportional to $1 - \exp(-KV_r^3)$, where K is a wavelength dependent constant. No satisfactory explanation of the observations could be presently provided.

1. *Introduction*

A suitably manufactured Schottky diode might be used as a high–efficiency photodetector. Such a photodiode is characterized by a depleted semiconductor region with a high electric field that separates photogenerated electron-hole pairs. It is usually illuminated through the metal contact, consequently the metal film must be very thin (< 10 nm) to avoid large (reflection and) absorption losses.

The photodiode can be unbiased during the operation (like solar cell), or it can be reverse-biased with reverse voltages low enough not to cause avalanche breakdown.

In this contribution, photodetection characteristics of Ag/n–Si(111) Schottky photodiode, prepared by the ionized–cluster–beam deposition of Ag^+ at an acceleration voltage equal to zero, is presented for three different wavelengths in the visible region. Also, the low reverse–bias dependence of the measured photocurrent is discussed.

2. *Sample preparation*

Ag/n–Si(111) Schottky diodes of various thicknesses and a diameter of 3.5 mm were prepared by the ionized–cluster–beam (ICB) deposition of Ag on Si. The description of the deposition method and its pertinent characteristics are presented in Refs. 1 and 2. Silicon surface was chemically cleaned (using the RCA cleaning method [3]) before inserting the wafer into the vacuum chamber. The silicon wafer was originally n–type, doped with phosphorus of a concentration of 10^{16} cm^{-3}. Silver was deposited without acceleration of Ag clusters ($U_a = 0$ V). The pressure in the vacuum chamber was 10^{-5} mbar (1 bar = 10^5 Pa). The silicon substrate was not heated prior and during the deposition. Thickness of the deposited Ag layer was 10 nm as measured by "TENCOR Alpha Step 200" surface profiler.

The photodiodes exhibit similar $I - V$ temperature dependence as normal 200 nm thick Ag/n-Si(111) ICB, $U_a = 0$ V deposited structures, an example of which is presented on Fig 1.

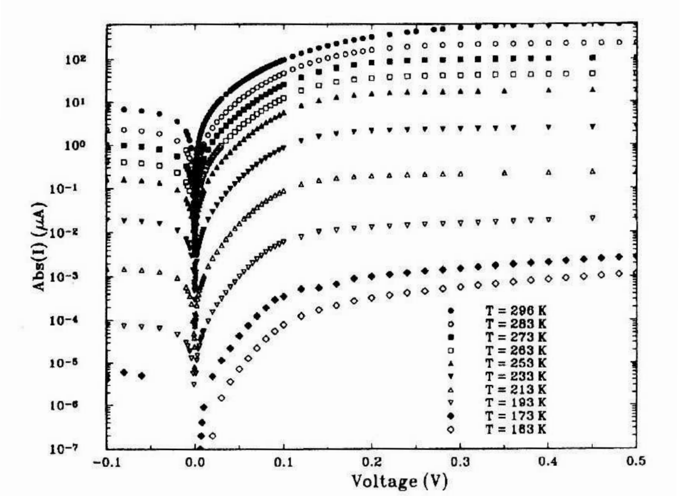

Fig. 1. $I - V$ characteristics of $U_a = 300$ V ICB deposited Ag/n–Si(111) *diode in the temperature range 160* K – *300* K.

The ohmic contact on the back side of the diode was made by the ICB method with the $U_a = 6$ kV acceleration voltage for Ag ionized clusters [2].

The selected diode was cut from the wafer and bonded to the copper coated vetronite with silver epoxy (EPO–TEK H20E). The electrical connections to the thin front side Ag layer of the diode were also achieved by the silver epoxy bonding of thin wires, that were cured for 90 minutes at 80° C in the vacuum chamber at pressure 10^{-2} mbar.

The described epoxy bonded contacts on the 10 nm thin Ag layer resulted in considerable change in the diode $I-V$ characteristics as measured before and after epoxy bonding. Prior to epoxy bonding, the diode had nearly ideal $I-V$ characteristics according to thermionic emission theory [4] ($n = 1.03$, $\varphi_b = 0.64$ eV), but after epoxy bonding, the ideality factor and, suprisingly, also the barrier height, φ_b, increased ($n = 2.4$, $\varphi_b = 0.67$ eV).

3. *Photocurrent measurements*

The diode photocharacteristics were measured in the range −5 V – 0 V using the "KEITHLEY 236 Source Measure Unit". An argon laser and a laser diode were used as light sources of monochromatic coherent light of wavelenghts, $\lambda = 488$ nm, 514 nm, 670 nm, respectively. The output power of the light sources were adjusted to be $P = 0.98$ mW for $\lambda = 488$ nm, $P = 0.90$ mW for $\lambda = 670$ nm and for $\lambda = 514$ nm, and the laser output power was: $P = 0.90$ mW, 1.17 mW and 1.53 mW.

The laser–light optical power arriving on the semiconductor surface, P_0, was calculated using the transmission coefficients for the 10 nm thick Ag layer [5]: $T(\lambda = 488 \text{ nm}) = 0.50$, $T(\lambda = 514 \text{ nm}) = 0.49$, $T(\lambda = 670 \text{ nm}) = 0.45$.

The $I-V$ characteristics of dark and illuminated diode are shown in Fig. 2a. The photocurrent at $V_r = 0$ V is ≈ 0.2 μA and saturates at $V_r \approx 1$ V. The quantum efficiency of the photodetector, defined as the number of the electron–hole pairs generated per incident photon, is given by [6]:

$$\eta = \frac{I_p/e_0}{P_0/h\nu} \quad , \tag{1}$$

where I_p is the measured photocurrent and $P_0 = T_\lambda \cdot P$ is the optical power that enters the semiconductor, $h\nu$ the photon energy, e_0 the unit charge and P is the output power of a light source. On Fig. 2b, the quantum efficiency as a function of reverse bias is presented. Another parameter of the photodiode, the responsivity [6, p.749], can also be stated. It is defined as the ratio of the detected photocurrent to the optical power (Fig. 2c):

$$\mathcal{R} = \frac{I_p}{P_0} \quad . \tag{2}$$

For low reverse voltages ($V_r < 1$ V), the responsivity also depends on the voltage, but saturates for $V_r > 2$ V (Fig. 2c).

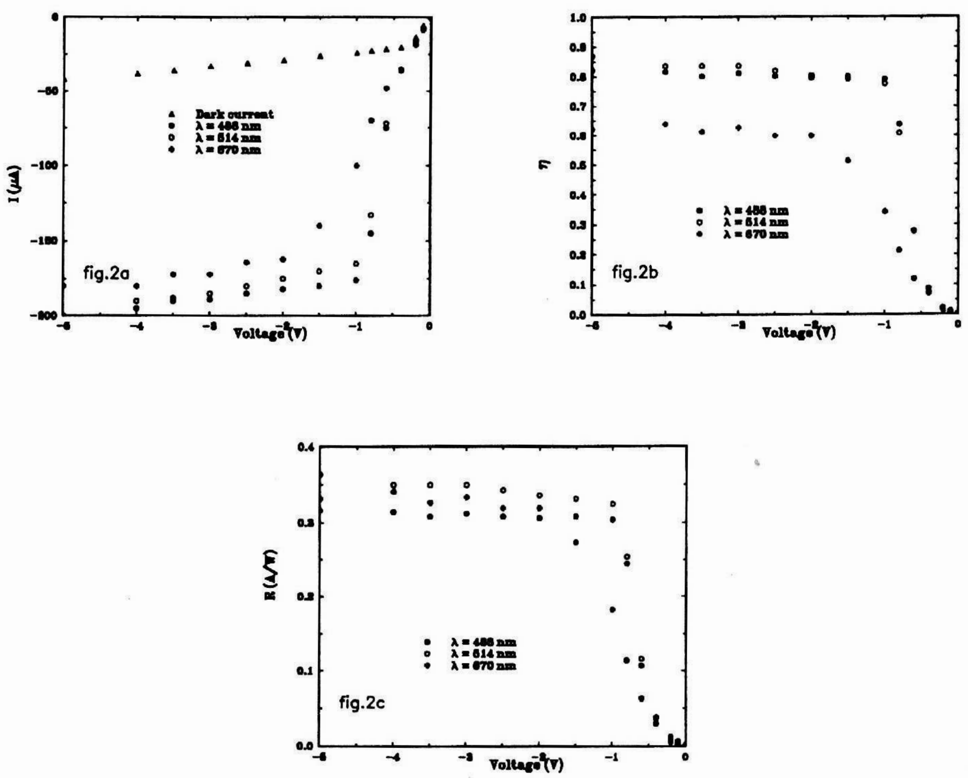

Fig. 2. (a) $I-V$ characteristics of Ag/n–Si(111) *Schottky photodiode showing both dark current and a regular current after illumination with laser light of approximately equal output power ($P \approx 1$* mW*) as a function of three different wavelengths, (b) voltage dependence of quantum efficiency and (c) voltage dependence of responsivity.*

4. Results and discussion

The reverse voltage dependence of the photocurrent for $U_a = 0$ of the ionized–cluster–beam deposited Ag/n-Si(111) Schottky photodiode is related to the voltage dependence of the width of the semiconductor space charge region, where the electron-hole pairs are photogenerated. Very low photocurrent at $V = 0$ V ($I_p = 0.2$ μA) shows that the width of the space charge region must be much smaller than the light penetration depth (l) for wavelenghts in the visible region. These depths are: $l(\lambda = 488 \text{ nm}) \approx 0.6\ \mu\text{m}$, $l(\lambda = 514 \text{ nm}) \approx 1.2\ \mu\text{m}$, $l(\lambda = 670 \text{ nm}) \approx 4\ \mu m$ [6]. It can be said that the depleted region at $V = 0$ V is much thinner than 0.6μm. If the only contribution to the space charge below and on the semiconductor surface were the ionized donors, the width of the depleted region would be equal to:

$$w(V) = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0^2 N_d}\big(\varphi_b - \xi - eV\big)} \quad ,$$

where ε is the dielectric constant of silicon, N_d is the donor density, φ_b the Schottky barrier height, ξ the energy difference between the semiconductor conduction band and semiconductor Fermi level and V the external bias. For $\varphi_b = 0.67$ eV, $N_d = 10^{16}$ cm^{-3}, $\xi = 0.2$ eV and $V = 0$ V, w equals to 0.25 μm which is comparable to l and consequently larger photocurrents would be expected.

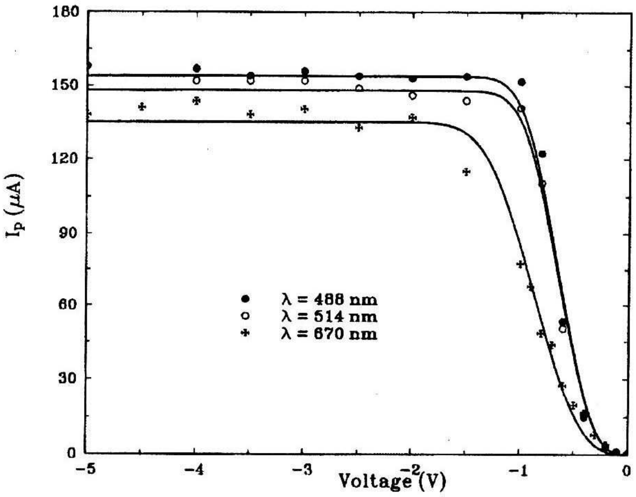

Fig. 3. Photocurrent ($I_p = I - I_{dark}$) voltage dependence of the Ag/n-Si(111) Schottky photodiode for three different wavelengths. The fit, as given by the Eq. (4) in the text, for an interval between -5 V *and 0* V*, is also presented for comparison.*

Additional reason that the above expression for the width of the space charge region is in our case inappropriate, is the fact that it predicts the wrong voltage dependence of the photocurrent, $I_p(V_r)$:

$$I_p = \eta\frac{e_0 P_0}{h\nu}\left(1 - \exp\Big(-\frac{w(0)}{l}\sqrt{1 - \frac{eV}{\varphi_b - \xi}}\Big)\right) \quad , \tag{3}$$

where $w(0)$ is the width of the depletion region at zero bias.

Photocurrent–voltage dependence, as seen in Fig. 3, turns out to be well described in terms of a fit which is given by

$$I_p = I_0\Big(1 - \exp\big(-KV_r^3\big)\Big) \quad + I_p(V_r = 0), \tag{4}$$

where I_0 is the saturation photocurrent and K is the fitting constant equal to 2.5 V^{-3} for $\lambda = 488$ nm and 514 nm, and 1 V^{-3} for $\lambda = 670$ nm (Fig. 3). This fitting shows that the width of the depletion region varies with V_r^3 rather than $V_r^{1/2}$. The underlaying physical mechanism for V_r^3 dependence of w is presently under investigation.

The responsivity of the $U_a = 0V$, ICB deposited Ag/n-Si(111) Schottky photodiodes is ≈ 0.35A/W which characterizes them as high sensitivity photodiodes in the reversed bias regime. It was established that the responsivity does not depend on the wavelength in the visible region (Fig. 2c), and also not on the laser output power.

5. *Conclusion*

The ionized–cluster–beam method for thin film deposition proved to be a suitable method for fabrication of high sensitivity Schottky photodiodes. The measured quantum efficiency for the Ag/n–Si(111) photodiode prepared by this method has been found to be nearly voltage dependence of the depletion layer width. The explanation of such $w(V)$ dependence very likely involves various effects beneath the surface of the diode that are caused by the metal deposition [2,7], however the reason for it is presently still unclear.

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POČETNA ISTRAŽIVANJA Ag/n–Si(111) SCHOTTKYJEVE FOTODIODE NAČINJENE SNOPOM IONIZIRANIH ATOMSKIH NAKUPINA

Izmjerena je foto-osjetljivost Ag/n-Si(111) Schottkyjeve fotodiode koja je načinjena snopom ioniziranih atomskih nakupina uz Ag^+ napon ubrzanja jednak nuli. Ustanovljena je visoka kvantna djelotvornost (do 85%) i osjetljivost od 0.35 A/W uz zaprečni napon. Za niske zaprečne napone (do 1 V) fotostruja pokazuje neobičnu ovisnost debljine sloja osiromašenja o naponu. Nije poznato objašnjenje tih opažanja.