The purpose of this work is to understand an important degradation mechanism in Schottky barrier photodetectors and solar cells. The I-V characteristics of Au-MOS devices under illumination show a pronounced photocurrent suppression at low voltages in the presence of an interfacial oxide layer of thickness \( \leq 20 \text{ Å} \) (intentionally introduced) but no suppression in the case of a carefully prepared near-intimate contact. The analysis of these devices takes into account the exchange of charge carriers between interface states and the metal (by tunneling) and between these states and the conduction and valence bands in the semiconductor. As suggested by the experiments, this shows that recombination in the interface states can be important only in the presence of a significant interfacial layer.

**DISCUSSION**

As noted previously (3), for MIS-Schottky barriers with ultra-thin oxide layers (\( \leq 20 \text{ Å} \)), interface states located at the silicon/oxide interface are in equilibrium with the metal. This means that for MIS-Schottky barrier photodetectors, when the interface states capture an optically generated hole, they release this hole to the metal before an electron can be captured from the conduction band to complete the recombination process. Interface states do not in this case constitute a recombination current and instead, this process contributes to the collected photocurrent.

The short-circuit energy band diagram for an MIS-Schottky barrier under illumination is shown in Fig.3(a). Photogenerated holes are supplied to the semiconductor surface by drift-diffusion processes represented by

\[
J_p = \rho \mu_p \frac{dE_p}{dx}
\]

(1)

For a sufficiently thin oxide (\( d \leq 20 \text{ Å} \)) these holes are readily removed by tunneling into the metal. Under these conditions the photocurrent collected obtains its maximum value, determined by the illumination level.
As the oxide thickness increases, the tunneling probability is diminished by the factor $\exp(-\chi d)$ where $\chi$ is the average potential barrier of the oxide for hole tunneling into the metal. For $d \geq 20 \text{A}$ (in the Au-SiO$_2$-nSi system) we have observed that the oxide begins to limit the collected photocurrent. The concentration of holes at the silicon surface increases and this reduces the net current supplied from the neutral region by increasing the diffusion of holes in the opposite direction. The quasi-Fermi level for holes becomes relatively flat in the depletion region ($E_{tp}$, $n(o)$ is small in (1)) and moves closer to $E_F$ at the surface.

At the same time the tunnel current of holes into the metal, given by (3)

$$J_t = \frac{4\pi e \chi q(ty)^2}{h^3 N} \exp(-\chi d) \quad (2)$$

increases due to the increase in $n(o)$, the hole concentration at the surface. A balance is struck for which, in the absence of significant recombination in interface states, $J_p = J_t$ and this occurs for a smaller current than was observed for thinner oxides, where the current was not tunnel-limited. We see therefore that suppression of the photocurrent collected at zero bias occurs for $d \geq 20 \text{A}$ even in the absence of interface states.

Let us now consider further the case of $d \geq 20 \text{A}$ and include the effects of interface state recombination. Under normal operating conditions, the hole concentration $n(o)$ at the surface is much greater than the electron concentration $n(o)$. This means that recombination in interface states (capture by these states of an electron followed by capture of an electron) is limited by the capture rate of electrons, which for states below the electron Fermi level $E_{Fn}$, is described by (6)

$$J_{rec} = qN\sigma(1-f)n(o) \quad (3)$$

where $N$, $\sigma$ are the density and electron capture cross-section of interface states, $v$ is the thermal velocity of electrons, $f$ is the occupancy function of interface states and $n(o)$ is the surface concentration of electrons. For typical values $N = 10^{13}$ states cm$^{-2}$, $\sigma = 10^{-15}$ cm$^2$ and $n(o) = 10^1$ cm$^{-3}$ (determined by a Schottky barrier height $\theta_{bh}$ of 0.6 eV for the Au-nSi device), $J_{rec} = 10^{-10}$ A cm$^{-2}$. This may greatly underestimate $J_{rec}$ for oxides with positive charges on the surface. Since $\theta_{bh}$ will be reduced from 0.8 eV and $n(o)$ will increase considerably. Large values of $\sigma$ have also been observed for interface states in these devices (7) under certain conditions (choice of metal, oxide thickness and sample annealing). Provided $J_{rec} \ll J_{tp}$, interface state recombination does not further suppress the photocurrent beyond that suppression due to the oxide layer alone. At low illumination levels, and for lower Schottky barrier height $\theta_{bh}$, interface recombination will have a major effect on photocurrent suppression for oxides $\geq 20 \text{A}$.

If the MIS-Schottky barrier photodetector is placed under a substantial reverse bias, part of the voltage will be developed across the oxide and this in turn reduces the effective barrier $\chi$. A larger tunneling probability will allow an increased $J_p$ and the hole concentration at the silicon surface will be depleted. This increases the net hole drift-diffusion current, $J_p$ towards the surface and $E_{tp}$ rises towards the metal Fermi level (Fig. 5(b)). For sufficient reverse bias, the short-circuit current is again limited by the photogeneration rate, the oxide-free case. It is thus clear qualitatively that for an MIS diode, the threshold reverse bias ($V_T$) for elimination of suppression increases with intensity because more tunnel current must be passed and for a fixed intensity, $V_T$ should increase with the oxide thickness. This is in accordance with experimental data shown in Fig. 6 for 3 different oxide thicknesses.

Further investigation is under way regarding the dependence of photocurrent suppression on oxide thickness and interface state parameters. We believe that the threshold $V_T$ for the complete collection of photocurrent and the shape of the photocurrent-voltage curves will help to a basic understanding of interface state processes.

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REFERENCES

Fig. 1. Schematic structure of the MIS-Schottky barrier (a) and the energy band diagram under thermal equilibrium (b).

Fig. 2. Reverse I-V characteristics of a near-ideal Schottky barrier. 1-4 represent progressively increasing illumination levels.
Fig. 4. Percentage of photocurrent collected as short-circuit current vs MIS oxide thickness under the same illumination intensity.

Fig. 3. Reverse I-V characteristics of an MIS-Schottky barrier (d = 35 Å). 1-4 represent progressively increasing illumination levels; these are not the same as in Fig. 2.
Fig. 5. Energy band diagram of an MIS-Schottky barrier under illumination in short-circuit condition (a) and under reverse bias until suppression is eliminated (b).

Fig. 6. Threshold reverse bias for no suppression vs photocurrent density for 3 different MIS oxide thicknesses.