Low temperature recombination lifetime in Si metal oxide semiconductor field effect transistors

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The recombination lifetime τ_r has been measured at low temperature in Si p-channel metal oxide semiconductor field effect transistors (MOSFET's) using the charge pumping technique. Measurements were performed over the 40–300-K range. A monotonically increasing lifetime with decreasing temperature was measured. τ_r was found to be proportional to $\exp(A_r/kT)$, where A_r is a constant determined from the slope of $\ln \tau$ vs $1/T$. For a typical MOSFET the lifetime ranged from 80 ns at 300 K to 370 μs at 100 K. The value of A_r in this case was determined to be 106 meV.

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The temperature dependence of the lifetime in Si is important both from a fundamental properties point of view and because of its role in the operation of metal oxide semiconductor field effect transistor (MOSFET) devices at low temperature. In this letter we report on the use of the charge pumping technique[1] to determine the recombination lifetime τ_r as a function of temperature in Si-MOSFET's. In charge pumping a narrow pulse is applied to the gate of the MOSFET, driving it briefly into inversion. During the pulse, inversion charge drawn from the source and drain fully populates the channel. When the pulse terminates, a fraction of the charge is injected from the channel into the substrate, where it recombines, resulting in a detectable substrate current. The average recombination current increases linearly with pulse frequency f_p until the pulse period is of the order of the recombination lifetime. The usefulness of this approach for low-temperature measurements is based on the fact that a ready supply of minority carriers is available and that the relaxation time is of the same order of magnitude as the lifetime.

p-channel MOSFET's with a channel length of 75 μm and a width-to-length ratio (W/L) of six were fabricated using an all ion-implanted process.[2] Low-temperature measurements were performed over the 40–300-K range using an Air Products Heli-Tran LT-3-110 system. For all the measurements reported here, charge pumping was performed by pulsing the gate from + 2 V (accumulation) to − 6 V (inversion) for 50 ns. To enhance the measurability of the lifetime effect, only the source was grounded with the drain left floating. This maximizes the fraction of the charge underneath the gate that recombines.

Typical charge pumping current I_{CP} dependence on pulse frequency is shown in Fig. 1. At 300 K and $f_p \gtrsim 1$ MHz, only a slight deviation from a linear I_{CP} vs $1/f_p$ relationship is observed. In contrast, at a temperature of 100 K, a marked falloff starting at $f_p \approx 1$ kHz is noticed. It is also important to point out that at low frequencies I_{CP} converges to roughly the same value at both temperatures. This confirms that the variation of I_{CP} with temperature is due mainly to the recombination lifetime. This point is shown more clearly in Fig. 2, where I_{CP} is plotted as a function of temperature for various frequencies. At 1 kHz a relatively temperature insensitive behavior is observed. The dependence of I_{CP} with temperature increases rapidly as the frequency is increased.

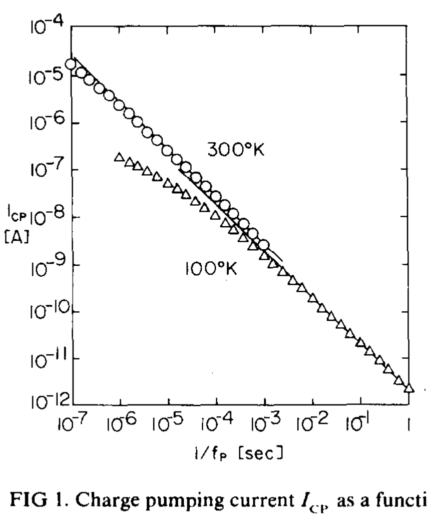

FIG 1. Charge pumping current I_{CP} as a function of the pulse period $1/f_p$ for a p-MOSFET.

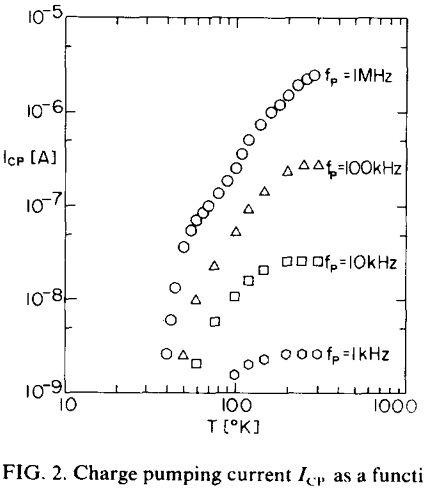

FIG. 2. Charge pumping current I_{CP} as a function of temperature at fixed frequencies.

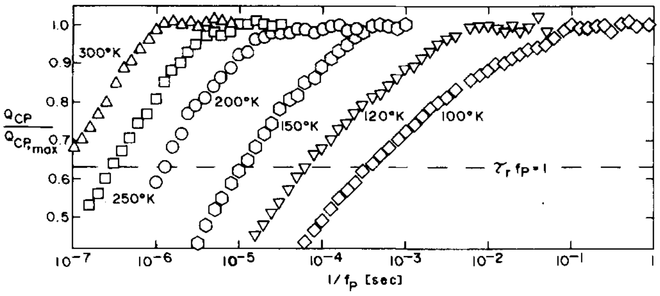

FIG. 3. Normalized charge pumping charge per pulse vs the pulse period over the temperature range 100–300 K.

The recombining charge per pulse $Q_{CP} = I_{CP}/f_p$ is more sensitive to the lifetime effect than I_{CP}. The low-frequency saturation level charge has a slight temperature dependence, making normalization of Q_{CP} necessary for proper comparison of the results at various temperatures. The normalized recombining charge is plotted as a function of the pulse period in Fig. 3 for six temperatures in the 100–300-K range. An identifiable "corner" frequency is seen to exist. The recombining charge per pulse decreases rapidly above this frequency. Following the model of Soutschek *et al.*,[3] the recombination lifetime is taken to be equal to the pulse period at which the normalized charge has fallen to 63% of its low-frequency value. τ_r ranges from 80 ns at 300 K to 370 μs at 100 K.

The recombination lifetimes determined from the data of Fig. 3 can be seen to vary exponentially with the inverse absolute temperature in Fig. 4. A straight line fit of the data yields $\tau_r \sim \exp(A_r/kT)$, where $A_r = 106$ meV. A_r appears to be an activation energy for the overall recombination process. This energy is clearly not associated with the major substrate dopant phosphorus, which has an ionization energy of 44 meV and should be fully ionized in this temperature range. It is, therefore, likely that the activation energy measured is associated with a hole trap. A tentative explanation for the recombination mechanism in that case would be as follows: (i) During steady-state accumulation (prior to the pulse) the traps are completely empty. (ii) When the pulse is applied, inversion is rapidly achieved due to a ready source of minority carriers, and the traps are completely filled with holes. (iii) When the device is switched back into accumulation, the mobile holes are rapidly returned to the source; recombination can then take place when a hole is emitted to the valence band and recombines with an electron through a recombination center. In this respect, our results are very similar to those of Wertheim[4] using photoexcitation techniques. He reported a trapping level of 110 meV above the valence band in n-type Si.

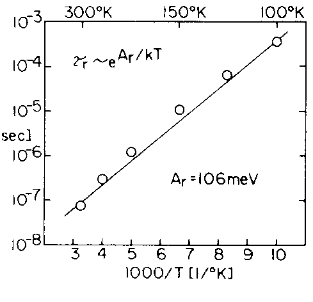

FIG. 4. Recombination lifetime τ_r vs 1000/T.

For comparison purposes, the generation lifetime τ_g was measured using the capacitance-time (C-t) technique and interpreted by Heiman's[5] method. This technique is not suitable at low temperatures due to the exceedingly long relaxation time. Data was obtained only over the 300-245-K range. At 297 K, τ_g was 1.1 μs, while τ_r was 0.1 μs. The difference in the values of the two lifetimes increases at low temperature. At 250 K, $\tau_g/\tau_r = 580$. The activation energy obtained from the log τ_g vs 1000/T plot is $A_g = 730$ meV. This is indicative of a recombination center located near midgap. Our results are similar to the results obtained by Schroder and Guldberg[6] using C-t measurements on metal oxide semiconductor (MOS) structures on n-type Si. They show an activation energy of about 734 meV for generation in the depletion region.

The viability of the charge pumping technique for determing the recombination lifetime in MOSFET's at low temperature has been demonstrated. Present instrumentation limits use of the technique to temperatures where the lifetime does not exceed tenths of milliseconds. The activation energy of the recombination process has been found to equal 106 meV. Transient capacitance measurements on the p-MOSFET indicate an activation energy of 730 meV for the generation process.

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