Carrier lifetime measurement on electroluminescent metal–oxide–silicon tunneling diodes

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(Received 13 February 2001; accepted for publication 20 July 2001)

The temporal response of the electroluminescence at the Si band gap energy from a metal–oxide–silicon (MOS) tunneling diode is used to characterize the minority carrier lifetime near the Si/SiO_2 interface. The temporal responses reveal that the Shockley–Read–Hall (SRH) recombination lifetimes are 18 and 25.8 μs for the rising and falling edges, respectively, and that the ratio for SRH, radiative, and Auger recombinations is 1:0.196:0.096 at injection current density of 39 A/cm^2. The investigation shows that the electroluminescence of the MOS tunneling diode can be significantly increased by reducing the number of the nonradiative recombination centers. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1405429]

When the dimensions of metal–oxide–semiconductor field-effect transistors (MOSFETs) are scaled down to the deep submicrometer level in state-of-the-art ultralarge-scale integration (ULSI) circuits, the thickness of the gate oxide is in the range of 15–30 Å.[1] Characterization of MOS devices with such thin gate oxides requires accurate determination of material parameters like the minority carrier lifetime near the Si/SiO_2 interface to give the information about the low defect densities present in the ULSI circuits. Conventional methods including high-low frequency capacitance–voltage analysis, the conductance method, the charge pumping method, and transient capacitance–time Zerbst analysis, etc. have been used to measure the minority carrier lifetime and the density of the interface states of MOS devices with relatively thick gate oxides.[2–4] However, as the thickness of the gate oxide shrinks, the leakage current tunneling through the ultrathin gate oxide increases. Therefore, the ultrathin oxide complicates the analysis and causes modeling based on the above measurement technologies to be difficult.[5–7] As a result, a new and simple method needs to be developed to characterize MOS devices with significant tunneling current. Optical methods, such as photoconductance and photoluminescence decay,[4,8,9] have been used to measure the minority carrier lifetime in Si. But the optical method is not suitable for the MOS structure because of the difficulty of optical pumping through the metal gate. In this letter, we report that the electroluminescence (EL) at the Si band gap energy[10–14] from silicon MOS tunneling diodes provides an easy way by which to probe the minority carrier lifetime and to provide related information about carrier recombination processes near the Si/SiO_2 interface.

Rapid thermal oxidation was used to grow ultrathin oxide on an *n*-type wafer with resistivity of 1–10 Ω cm. The fabrication process is similar to previously reported ones.[10–14] The peak emission energy of the EL is around 1.08 eV.[10–14] The temporal response of the EL under injection of a square current pulse was measured using a scanning-gate integrator and a boxcar averaging system.[15] The experimental setup is schematically shown in Fig. 1. A MOS light-emitting diode was driven by a square pulse current generated from an HP8114A. An InGaAs detector with a diameter of 5 mm was placed close to the MOS light-emitting diode to collect the luminescence. A preamplifier (model SR445, Stanford Research Systems) with 300 MHz bandwidth was used to amplify the signal. The amplified signal was sent to a SR250 gated integrator and the boxcar averager. The gated integrator integrates and normalizes the signal during the gated period. The boxcar averages the output over many shots of injection current. The gate delay was scanned by applying a control voltage from a SR200 gate scanner to allow retrieval of the entire EL wave form. The bandwidth of the overall measurement system was tested by a commercial light-emitting diode, which typically has modulation bandwidth far above several MHz. The response time of the overall measurement system was found to be much faster than the temporal response of the MOS light-emitting diodes. This ensures the feasibility of wave form retrieval of the EL signal using the scanning gate integrator and boxcar averager.

The temporal response of the EL under injection of a square current pulse of 150 μs duration is shown in Fig. 2. Figure 2(a) shows the typical wave form of the injection

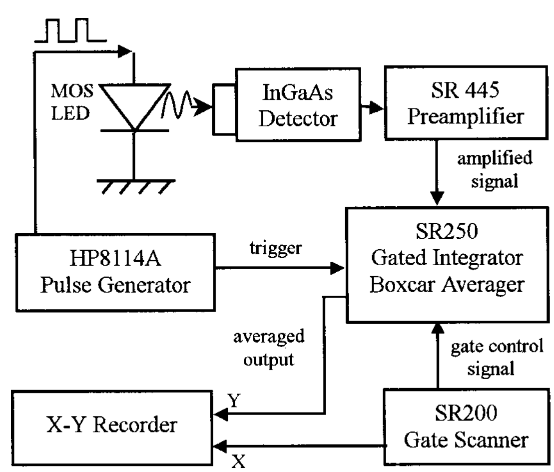

FIG. 1. Schematic of the experimental setup for the measurement of temporal response.

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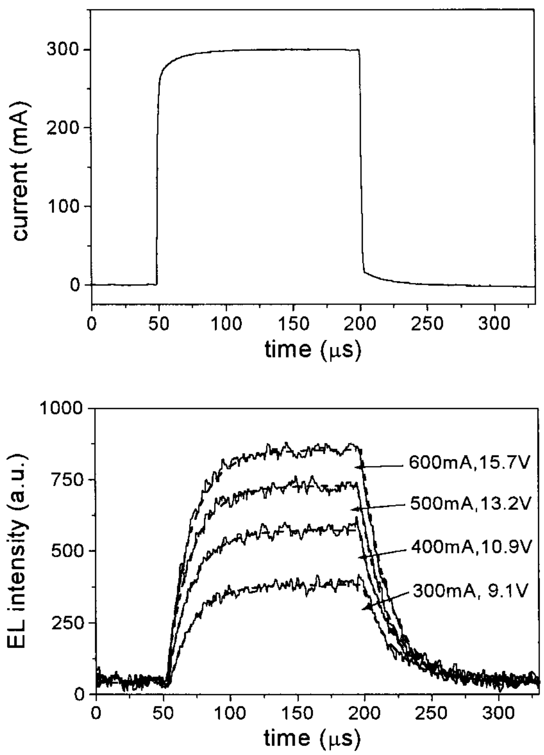

FIG. 2. (a) Typical wave form of the injection current with a duration of 150 μs and (b) temporal EL wave form from the MOS tunneling diode at various injection currents.

current. Figure 2(b) shows the measured temporal wave forms of the EL from the MOS tunneling diode at various injection currents. The measured temporal EL signals track the variation of the excess minority carrier density over time.[4] Because of the *RC* time constant of the MOS structure, the injection current pulse rises and falls in a sluggish manner rather than in the very fast response time (~10 ns) of the HP8114A. However, a comparison of Figs. 2(a) and 2(b) shows that the temporal response of the injection current pulse is still much faster than the response of the EL signal. Therefore, the minority carrier lifetime at the Si/SiO_2 interface can be determined by either the rising edge or the falling edge of the EL response curve.

The theoretical fitting curves in Fig. 2(b), indicated by the thick dashed lines, are obtained by solving the following equation:[4]

$$\frac{dP}{dt}=G-(AP+BNP+CN^2P), \tag{1}$$

where P is the excess minority carrier density, N is the majority carrier density, and G is the generation rate of the excess minority carrier density due to the injection current. A is the coefficient of the Shockley–Read–Hall (SRH) recombination through the states near the Si/SiO_2 interface. B and C are band-to-band radiative recombination and Auger recombination coefficients, respectively. The rising and falling edges of the temporal EL wave forms were fitted using the exponential function with the time constant τ related to coefficients A, B, and C:

$$\frac{1}{\tau}=A+BN+CN^2. \tag{2}$$

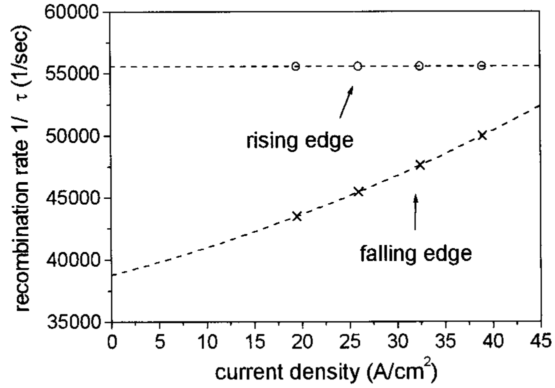

FIG. 3. Total carrier recombination rates $1/\tau$ vs the injected current level at the EL rising and falling edges. The dashed lines are the theoretical fitting.

Figure 2(b) shows a good match between the experimental data and the fitting curves. The total carrier recombination rates $1/\tau$ extracted from the curve fitting in Fig. 2(b) are shown in Fig. 3. The values of τ deduced are in agreement with the minority carrier lifetime of 1–100 μs for state-of-the-art ULSI technology.[3] At the rising edge of the EL, the recombination rate is independent of the injection current level. This can be attributed to the dominant process of SRH recombination according to Eq. (2). On the other hand, the recombination rate slightly increases with the injection current at the falling edges of the EL signal. Since the majority carrier density at the accumulation layer increases with applied voltage, this indicates that the effect of radiative and Auger recombination cannot be neglected at the EL falling edge.

It is known that Si/SiO_2 interface states with energies near the Fermi level are the most active SRH recombination centers[2–4] and that the SRH recombination rate approaches a maximum when the recombination centers are near the midgap region.[16] Just as the current is turned on (rising edge), the MOS diode is still near the flat-band condition and the position of the Fermi level is close to midgap. Thus the SRH recombination rate is large and depends less on the carrier density N because there is no large accumulation of carriers near the Si/SiO_2 interface. At the falling edge, the MOS is already at the accumulation region. Then the Fermi level in *n*-type Si is located near the conduction band edge, leading to the reduced SRH recombination rate, compared to that the rising edge. Also, the Fermi level has negligible variation with the injection current, so the SRH recombination is constant in the case of the accumulation region. In addition, the near-conduction-band Fermi level results in a very large accumulated majority carrier density. This causes the relatively strong influence of carriers on the recombination rate.

As shown in Fig. 3, the recombination rate at the EL falling edge superlinearly increases with the injection current. Using the least squared method, a parabolic curve can fit these data points well. The relation between current density J and carrier density N is usually given by $J=TqNv$,[17] where T is the tunneling probability across the oxide. Its value depends on the oxide voltage V_{ox}.[4,17] Figure 4 shows the calculated V_{ox} vs V (the total applied voltage across the MOS tunneling diode) using the equations of tunneling current in Ref. 4. The thickness of the gate oxide is 30 Å, the gate area is 0.0154 cm^2, and the resistance of the Si substrate

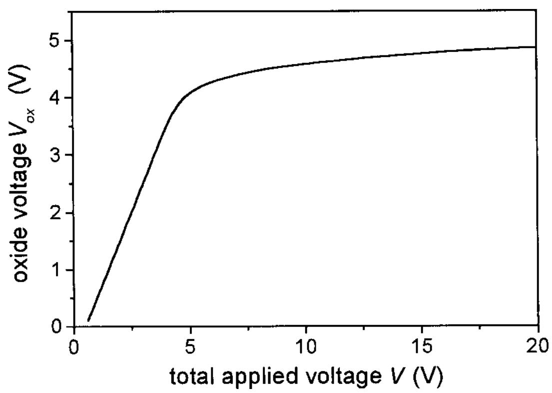

FIG. 4. Calculated oxide voltage vs total applied voltage.

is ~15 Ω, respectively. When V is greater than 5 V, the major voltage drop is on the Si substrate due to the high injection current, so the increase of the oxide voltage V_{ox} is small. Hence, at large applied voltages, the tunneling probability T approaches a constant[4] to give an approximately linear relation between the current density J and the carrier density N, $N=kJ$. Thus Eq. (2) gives the parabolic relation between the recombination rate $1/\tau$ and current density J:

$$\frac{1}{\tau}=A+BkJ+Ck^2J^2. \tag{3}$$

Therefore, the measurements shown in Fig. 3 reveal the relative roles of SRH recombination, radiative recombination, and Auger recombination.

From the intercept of the fitting curves in Fig. 3 and from Eq. (3), the SRH recombination lifetimes τ_{SRH} ($\tau_{SRH}=1/A$) are 18 and 25.8 μs for the rising and falling edges, respectively. The parabolic curve in the falling edge also gives the values of Bk and Ck^2, which are 194.6 $cm^2/A\,s$ and 2.4 $cm^4/A^2\,s$, respectively. The ratio for SRH, radiative, and Auger recombinations is 1:0.196:0.096 at injection current density of 39 A/cm^2. In the falling edge, the SRH recombination is still the most important process, but the contributions from radiative and Auger recombination cannot be ignored. Our study reveals that reducing the number of SRH recombination centers should improve the EL efficiency of the MOS tunneling diode.

If the Auger recombination coefficient $C=10^{-31}\,cm^6/s$ for holes in bulk Si is used,[4] the value of coefficient B can be determined to be $4\times10^{-14}\,cm^3/s$. It is about 10 times larger than that reported for bulk silicon.[4] The increased radiative recombination could be due also to the assistance of interface roughness and localized carriers for MOS tunneling diodes.[10–13]

In conclusion, the temporal response of a light-emitting MOS silicon tunneling diode was measured. The minority carrier lifetimes were deduced from the temporal EL wave forms. At the rising edge of the EL, SRH recombination is the only significant process, while at the falling edge radiative and Auger recombination show importance. The study indicates that reducing the number of nonradiative recombination centers should increase the electroluminescence of a MOS tunneling diode.

This work was supported in part by the National Science Council, Taipei, Taiwan, Republic of China, under Contract Nos. NSC89-2215-E-002-016, NSC89-2112-M-002-034, and 88-2218-E-002-004.

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