Roughness-Enhanced Electroluminescence from Metal Oxide Silicon Tunneling Diodes

C. W. Liu, *Member, IEEE*, M. H. Lee, Miin-Jang Chen, Ching-Fuh Lin, *Senior Member, IEEE*, and M. Y. Chern

***Abstract*—An approximate two-order increase in magnitude in electroluminescence was observed for the metal–oxide–silicon tunneling diodes with oxide grown at 900 °C, as compared to 1000 °C. The x-ray reflectivity revealed that the oxide grown at 900 °C has rougher interface than that grown at 1000 °C. The role of interface roughness can be understood in a model composed of phonons and interface roughness. An external quantum efficiency of $\sim 10^{-6}$ was obtained using Al electrodes.**

***Index Terms*—Electroluminescence, metal oxide silicon diode, roughness.**

I. INTRODUCTION

THE integration of light emitters and detectors in a CMOS-compatible process makes the optical interconnects feasible for ULSI circuits [1], [2]. Two different Si light emitters have been reported. A narrowband infrared emitter at 1160 nm was implemented using a pn junction under forward bias with external quantum efficiency of $\sim 10^{-4}$ [3]. A broadband (450 to 850 nm) visible-light emitter was also realized using an avalanche pn diode with external quantum efficiency of $\sim 10^{-8}$ [3] and $\sim 10^{-6}$ [4]. Recently, the band-edge electroluminescence (EL) of a MOS tunneling light emitting diode (LED) has also been reported [5]. The same MOS tunneling structure was also used as a photodetector [6]. Due to the indirect bandgap of Si, the additional momentum is required for the light emission process. The phonon provides the additional momentum in bulk Si [7] and bulk SiGe [8]. Besides phonons, theoretical work shows that the roughness can enhance the visible light emission by a factor of ~10 in the MOS structures under a specific condition [9, Fig. 10], but the magnitude of increase for the band-edge emission due to the interface roughness is not reported. In the MOS structure, the interface/surface roughness can seriously affect the transverse carrier mobility in the inversion layer [10]. This indicates that the interface/surface roughness can scatter the carrier and can change the carrier momentum. Therefore, we grow the ultrathin oxide of MOS devices at different temperature with different roughness and demonstrate that the rougher MOS device has much higher emission intensity.

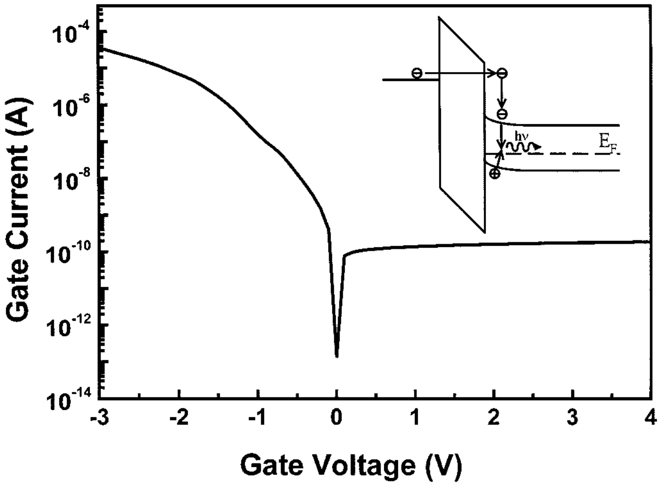

Fig. 1. *I–V* characteristics of an NMOS diode on the p-type (100) substrate with an area of 3.2×10^{-4} cm^2. The oxide thickness is 2.5 nm. The inset is the schematic band diagram of light emission process.

II. DEVICE FABRICATION

The ultrathin gate oxide of the NMOS diode was grown by rapid thermal oxidation on 1 to 10 Ω-cm p-type wafer at the 900 and 1000 °C. The gas flows are 500 sccm nitrogen and 500 sccm oxygen at a reduced pressure. After a HF dip, the wafer is *in-situ* baked in hydrogen at 1000 °C for 1 min. The oxide thickness is measured by ellipsometry. The roughness is measured by x-ray reflectivity and is extracted by a commercial program. The NMOS LED had Al gate electrodes with circular areas defined by photolithography. Another contact is on the back of the wafer.

III. DEVICE OPERATION

Fig. 1 shows the current–voltage (*I–V*) characteristics of an NMOS tunneling diode. For the Al gate under negative bias, the electron in the Al tunnels to the Si substrate through the ultrathin oxide. For the magnitude of the negative gate bias less than 1 V, the electron tunnels to the interface states in the Si/oxide interface [11], and thus can not contribute to the band-edge light emission process. For the magnitude of the negative gate bias larger than 1 V, the electron starts to tunnel into the conduction band of Si substrates. The negative gate bias also attracts the holes at the Si/SiO$_2$ interface to form an accumulation re-

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C. W. Liu and M. H. Lee are with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C., and also with the Graudate Institute of Electronics, Taipei, Taiwan, R.O.C (e-mail: chee@cc.ee.ntu.edu.tw)

M.-J. Chen and C.-F. Lin are with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C., and alsow with the Institute of Electro-Optical Engineering, Taipei, Taiwan, R.O.C.

M. Y. Chern is with the Department of Physics, National Taiwan University, Taipei, Taiwan, R.O.C.

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TABLE I
EXTRACTED OXIDE THICKNESS, INTERFACE ROUGHNESS, AND SURFACE ROUGHNESS BY THE FITTING OF REFLECTIVITY. THE THICKNESS MEASURED BY ELLIPSOMETRY IS ALSO LISTED FOR COMPARISON

Growth temperature	Oxide thickness (by ellipsometry)	Oxide thickness	Interface roughness	Surface roughness
1000°C	3.5nm	3.5nm	0.35nm	0.4nm
900°C	2.2nm	2.5nm	0.5nm	0.55nm

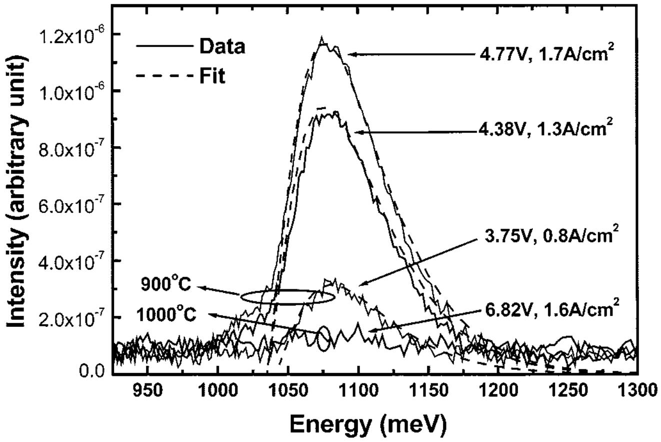

Fig. 2. EL spectra of MOS diodes with oxide grown at different temperature.

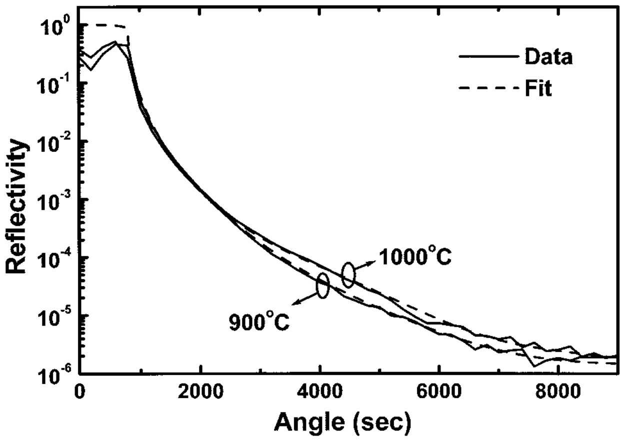

Fig. 3. Reflectivity measurements of rapid thermal oxide grown at different temperature. The rougher interface/surface makes the curve to drop faster.

gion. The holes in the Si valence band become localized along the growth direction and its momentum has a spread in the reciprocal space along the growth direction. The tunneling electrons in the Si conduction band can recombine with the holes in the accumulation region, and light is emitted if the momentum can be conserved by phonons and interface/surface roughness (the inset of Fig. 1). Note that there is a kink at ~ -1 V in the *I–V* curve of the NMOS device, indicating the transition of these two current-transport mechanisms. The results of the EL measurement for the 900 °C-grown-oxide sample and the 1000 °C-grown-oxide sample with the size of 4×10^{-2} cm^2 are shown in Fig. 2. The 900 °C sample with oxide thickness of 2.5 nm has an infrared emission and its line shape can be fitted by an electron-hole plasma (EHP) model [5], while little electroluminescence signal is detected for the 1000 °C sample under a similar current density. The 900 °C sample emits approximately two orders of magnitude of light, as compared to 1000 °C sample. The emission intensity increases for 900 °C sample as the applied voltage increases. Due to the bulk resistivity (1–10 Ω-cm) of Si used in the study, the series resistance of both devices is about 2–16 Ω. At the high drive current density (0.8–1.7 A/cm^2, Fig. 2), there is a significant voltage drop on the Si, and this leads to a weak dependence of the gate current on gate voltage. Note that the gate current increases by a factor of two when the gate voltage increases from 3.75 to 4.77 V, while at least two orders of magnitude would be expected for the 2.5-nm thick oxide if series resistance were neglected.

IV. ROUGHNESS AND EMISSION MODEL

The x-ray reflectivity is used to measure the roughness of the rapid thermal oxide. Using Born approximation and a Gaussian distribution of interface/surface displacement, the reflectivity amplitude is given by

$$r = r_F \exp\left(-\frac{1}{2}\left(\frac{4\pi\sigma\theta}{\lambda}\right)^2\right)$$

where

σ	root-mean-square(rms) value of roughness;
λ	x-ray wavelength;
θ	angle between incident beam and oxide surface.

The interface roughness is the roughness between oxide and silicon, and surface roughness is the roughness between oxide and air. Due to the conformality of surface oxide to the underlying Si surface morphology [12], the interface roughness and surface roughness should be correlated, i.e., the rougher surface has the rougher interface. Fig. 3 is the reflectivity data for the oxides grown at 900 and 1000 °C. The reflectivity drops faster for the rougher interface and surface. The interface roughness, surface roughness and oxide thickness extracted by a commercial fitting program [13] are listed in Table I. The extracted thickness values are similar to those obtained from ellipsometry. Both interface and surface of the 900 °C-grown sample are rougher than those of the 1000 °C-grown sample. Since the electron and hole recombination occurs in Si/oxide interface, the interface roughness seems to be more important than the surface roughness for the momentum conservation in the radiative process. The MOS device with rougher interface (900 °C-grown oxide) emits more intense light. This indicates that interface roughness can enhance the light emission process.

Reference [7] shows that the band-edge emission from MOS light emitting diode is due to the phonon-assistant process (phonon replica), and the photon energy emitted is slightly lower than Si bandgap. Therefore, both interface roughness

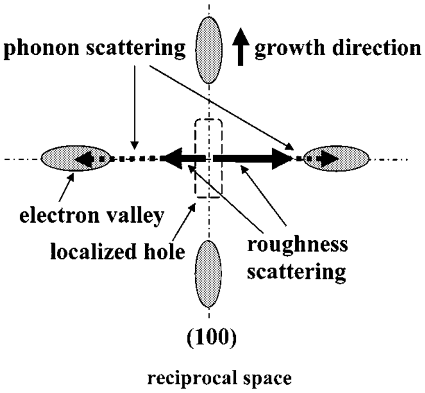

Fig. 4. Picture of the radiative recombination in a MOS tunneling diode on (100) Si surface. Note that the two valleys perpendicular to the paper are not shown.

and phonons are involved in the radiative process. A picture of the radiative process composed of phonons and interface roughness for the device biased in the accumulation region is given in Fig. 4. Without roughness scattering, phonons with momentum of the exact 0.85 $(2\pi/a)$, where a is the Si lattice constant, have to carry holes from the valence band edge into the electron valleys or to carry electrons from electron valley into the valence band edge during the light emission. The latter process is not shown in Fig. 4 for simplicity. With the interface roughness, the phonon and interface roughness together can provide the 0.85 $(2\pi/a)$ momentum. Due to the randomness nature of roughness, the momentum of roughness has a two dimensional distribution in the reciprocal space [10]. Therefore, more phonons with momentum complementary to interface roughness scattering can be involved in the light emission process and thus more light is emitted. Note that due to the geometry of the six electron valleys in Si, the light emission from the four electron valleys perpendicular to the growth direction (100) is enhanced by the roughness. The external quantum efficiency measured from the edge of the Al gate electrode with the Al back contact is around 10^{-6} for the 900 °C sample. Beside the magnitude of the interface roughness, the spatial spectrum of the interface roughness is also important. Obviously, with the same magnitude of roughness, the wider spectra should enhance more for the light emission. In the literature, the spatial spectrum has been measured by atomic force microscopy (AFM) and mobility measurement [10]. Although there are quantitative discrepancies between these two methods, both measurements show that the oxides grown at different conditions have similar bandwidths in interface roughness spectra. We, therefore, assume that the interface-roughness spectra of both devices have similar bandwidths.

V. CONCLUSION

We have demonstrated that the use of roughness of Si/oxide interface can increase the band-edge electroluminescence in a metal–oxide–silicon tunneling diode. The rougher interface associated with the rapid thermal oxide can be grown at 900 °C, as compared to 1000 °C. This novel LED may open new applications of MOS devices.

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