Temperature dependence of the electron–hole-plasma electroluminescence from metal–oxide–silicon tunneling diodes

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The temperature performance of metal–oxide–silicon tunneling light-emitting diodes was studied. An electron–hole-plasma model can be used to fit all the emission spectra from room temperature to 98 K. At constant voltage bias in the accumulation region, the normalized integral emission intensity slightly increases at low temperature with activation energy as low as 12 meV. From room temperature down to 98 K, the extracted band gaps are ~80 meV lower than the value of Varshni equation, and the linewidth drops from 65 to 30 meV. The transverse optical and longitudinal optical phonons are involved in the light-emission process due to the reduction of extracted band gaps and the resemblance between electroluminescence and photoluminescence spectra at similar temperature. © *2000 American Institute of Physics.* [S0003-6951(00)01934-3]

Although light emission from metal–oxide–silicon (MOS) diodes has been observed, most luminescence originates from defect-related mechanisms.[1,2] Until recently, we reported band-edge electroluminescence (EL) (Ref. 3) in both *n*-type (NMOS) and *p*-type (PMOS) tunneling diodes. An electron–hole-plasma (EHP) recombination model was given to probe the line shape of the electroluminescence, and the band-edge luminescence nature was confirmed at room temperature.[4] The low-voltage operation capability (<3 V) makes the MOS light-emitting diode (LED) suitable for dual-mode optical interconnects of future ultra-large-scale-integrated circuits.[3] To further study the characteristics of the MOS LED, we performed a temperature dependence study on a PMOS diode. Previous studies[5,6] on both SiGe/Si LEDs and Si/SiGe/Si quantum wells showed that the emission intensity increased as the temperature decreased and saturated at low temperature for constant carrier injection. To maintain an injection current at low temperature in Si/SiGe *p*-type-intrinsic-*n*-type diodes, the applied voltage has to be increased. For the MOS LED, the injection current can be maintained at low temperature without increasing the applied voltage due to the tunneling nature of the carrier injection. Given a constant voltage bias, the tunneling injection makes this MOS LED particularly suitable for low-temperature applications.

The ultrathin gate oxide of the MOS tunneling diode used in this study is grown by rapid thermal oxidation at 900 °C. The gas flows are 500 sccm nitrogen and 500 sccm oxygen at a reduced pressure. Before oxidation, the sample was cleaned by a HF dip. The thickness was measured by ellipsometer. The resistivity of the 100 mm *n*-type wafers is 1–10 Ω cm. The PMOS diodes had Al gate electrodes with circular areas defined by photolithography.

Figure 1 shows current–voltage curves of an Al/2.7 nm oxide/*n*-silicon PMOS diode with a circular area of $4\times10^{-2}\,\mathrm{cm}^2$ at different temperatures. Device temperatures of 228, 180, 140, and 98 K are obtained from fitting of the EL line shapes, while the temperatures of the cold finger in the EL measurement are 200, 150, 100, and 10 K, respectively. The temperature difference is due to the device heating. The EL spectra at 98 K (the cold finger at 10 K) has a similar line shape to the photoluminescence (PL) spectra at 100 K at a pump power of 35 W/cm^2 (Fig. 2). Note that the sample temperature of the PL measurement should be close to that of the cold finger at this pump power.[6] The emission spectra from 300 K down to 98 K are shown in Fig. 3 with a fixed gate bias of positive 3 V and a drive current density of ~0.4 A/cm^2. To ensure no degradation of the device due to current stress of the ultrathin oxide, the current–voltage curves were measured before and after the EL measurements. Little change of the current–voltage curves was observed for such low drive current density. The electroluminescence spectra at all measurement temperatures can be fit by the line shapes of the EHP recombination using the following expression:

$$I(h\nu)=I_0\int_0^{h\nu-E_{g,EL}} dE D_e(E) D_h(h\nu-E_{g,EL}-E)$$
$$\times f(E,F_e,T) f(h\nu-E_{g,EL}-E,F_h,T),$$

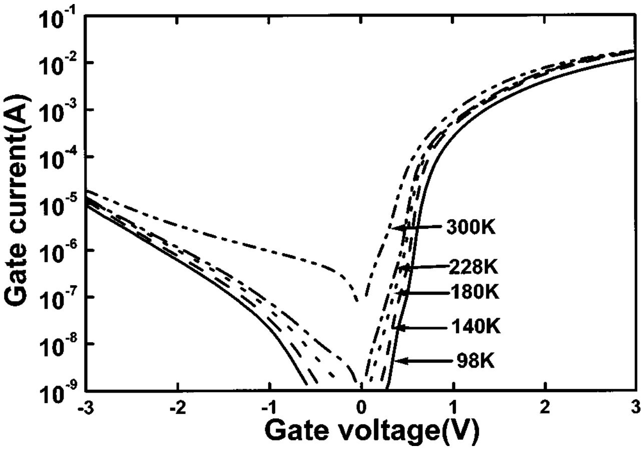

FIG. 1. Current–voltage characteristics at different temperature for the MOS LED.

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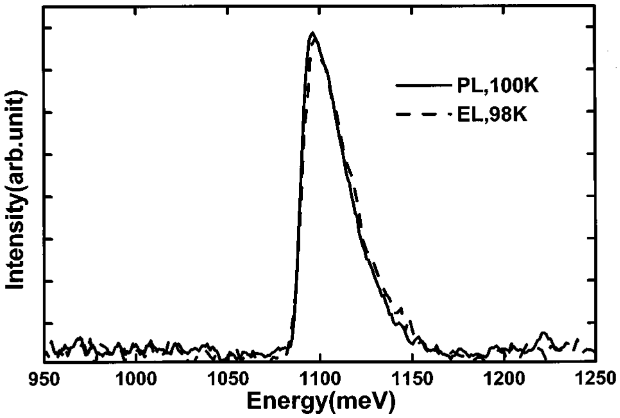

FIG. 2. Comparison between the EL spectrum at 98 K and the PL spectrum at 100 K.

where D_e and D_h are the densities of states of electrons and holes, respectively, F_e and F_h are the respective quasi-Fermi energies, $h\nu$ is the energy of photon emitted, T is the measurement temperature, $E_{g,\mathrm{EL}}$ is the band gap of Si obtained by the EL measurements, and f's are the Fermi–Dirac distribution. Note that only the conservation of energy is taken into account in this expression, assuming that momentum conservation is achieved by Si/oxide roughness, localized holes, phonons, and other possible mechanisms.[4] The three-dimensional (3D) density of states $[D(E)\sim E^{1/2}]$ is used for holes, while a constant two-dimensional (2D) density of states is used for electrons in the accumulation layer. Table I lists the fitting parameters (temperature, electron quasi-Fermi energy, hole quasi-Fermi energy, and band gap) of EL spectra at different temperatures as well as the hole density in the oxide/Si interface estimated from the Fermi energy. Note that the electron density in the accumulation layer is two-dimensional, and the effective (3D) density (2D density divided by accumulation layer thickness) should be similar to the hole density due to charge neutrality. The theoretical line shape is a convolution between the electron population and the hole population, distinct from the free-exciton line shape [$\sim E^{1/2}\exp(-E/kT)$, where E is the photon energy and k is the Boltzmann constant].[7] According to the Mott transition, excitons are formed at a low carrier density, while at a high carrier density, excitons dissociate into electron–hole plasma. The transition density is given by $kT/16\pi E_x a_x^3$,[7] where E_x is the Rydberg exciton, and a_x is the Bohr exciton radius. At 98 K, the transition density is $\sim 1\times 10^{17}\,\mathrm{cm}^{-3}$, while the carrier density estimated from the quasi-Fermi hole energy at 98 K in Table I is $\sim 2\times 10^{18}\,\mathrm{cm}^{-3}$. Therefore, free excitons cannot be observed at 98 K, while the thermal energy (8.5 meV) is still lower than the exciton binding energy (14.7 meV). The normalized emission intensity (the ratio of the integral intensity to the drive current) has weak temperature dependence and slightly increases at low temperature (Fig. 4). The activation energy obtained from the Arrhenius plot is 12 meV. As a comparison, the previous PL results[6] showed that a large activation energy (150 meV–280 meV) of PL intensity in Si/SiGe/Si quantum wells was observed, corresponding to the band-gap difference between Si and SiGe. The hole concentration in the SiGe well drops at high temperature, and this yields a lower recombination rate in the SiGe well. However, in the MOS LED, the electron concentration in the accumulation region of the *n*-type Si is mainly determined by the positive gate voltage, which is independent of temperature. This yields, relatively weak temperature dependence of EL integral intensity in the MOS LED.

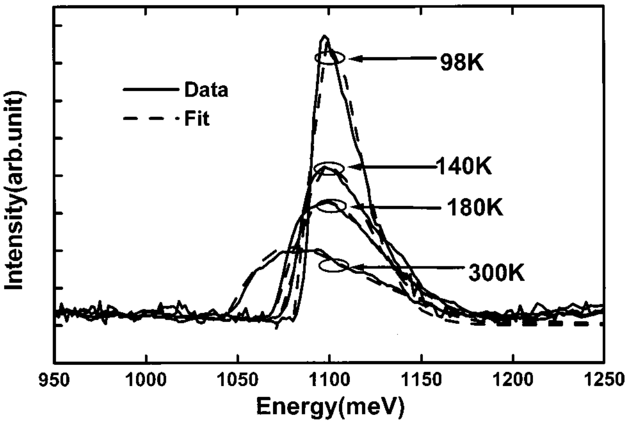

FIG. 3. EL spectra of the MOS LED at different temperatures.

TABLE I. Fitting parameters obtained from EL spectra as well as the hole density.

T (K)	F_n (eV)	F_p (eV)	$E_{g,\mathrm{EL}}$ (eV)	Hole concentration (cm^{-3})
300	-0.088	-0.07	1.04	6×10^{17}
228	-0.058	-0.049	1.062	5×10^{17}
180	-0.025	-0.011	1.06	2×10^{18}
140	-0.010	-0.008	1.073	1×10^{18}
98	0.005	0.005	1.08	2×10^{18}

The extracted band gaps from EL spectra are ~80 meV lower than the Si band gap obtained from the Varshni equation[8] at all temperatures (Fig. 5). The transverse optical (TO) phonons as well as the longitudinal optical (LO) phonons are probably involved in the light-emission process. This phonon participation is confirmed by the resemblance between the EL spectrum at 98 K and the PL spectrum at 100 K (Fig. 2), since it is well known that the Si PL peak is due to phonon replicas. In PL spectra at very low temperature (2 K), both TO (58 meV) and LO (56 meV) phonon replicas were observed, but the TO emission intensity is about three times that of the LO emission. For EL and PL

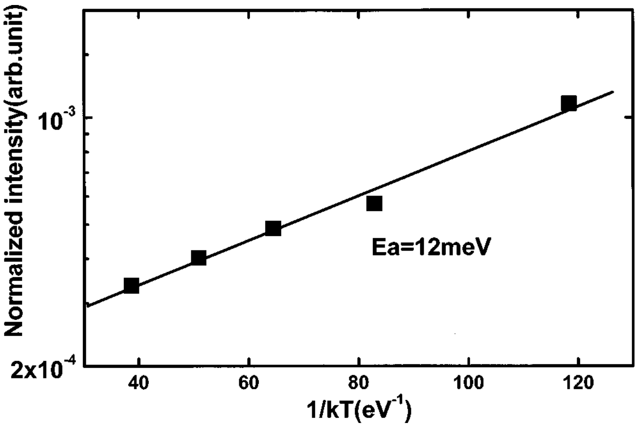

FIG. 4. Arrhenius plot for the normalized integral intensity of the MOS LED biased at 3 V.

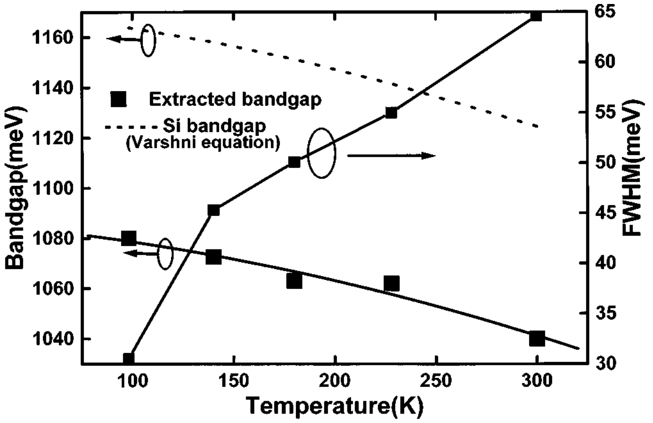

FIG. 5. Extracted band gap and linewidth at different temperatures. Si band-gap data are obtained from the Varshni equation of Ref. 8.

spectra measured at 77 K or higher, these two close lines (only 2 meV apart) are not resolved, and one effective line shape can fit the experimental data reasonably well in the SiGe PL,[7] as well as in the Si EL of this work. The rest of the band-gap lowering (~20 meV) may be due to the surface bending[4] and/or the band-gap narrowing at high carrier density.[9] The peak widths (full width at half maximum) of the EL spectra decreases from 65 to 30 meV for the temperature from room temperature to 98 K (Fig. 5). This is due to the carrier filling close to the conduction-band and valence-band edges at low temperature as a result of the Fermi–Dirac distribution.

We also measured the external quantum efficiency of the MOS LED using Al as the gate electrode as well as the back contact. The external quantum efficiency is about 10^{-6} at room temperature, measuring from the edges of the Al electrode. Although the Auger recombination can degrade the carrier lifetime, the external quantum efficiency does not drop up to the injection current of 100 mA. A previous simulation study on SiGe PL shows that the Auger recombination seems important at low temperature, not at room temperature[10] at the pump power of 30 W/cm^2.

In conclusion, the emission intensity of the MOS LED has weak temperature dependence from room temperature down to 98 K, and increases slightly at low temperature. The emission peak is due to TO phonons as well as LO phonons. The emission process at all temperatures can be fit by the EHP model. A relatively intense EL from the MOS LED is observed, as compared to the PL.

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[1] Y. Q. Wang, T. P. Zhao, J. Liu, and G. G. Qin, Appl. Phys. Lett. **74**, 3815 (1999).
[2] J. Yuan and D. Haneman, J. Appl. Phys. **86**, 2358 (1999).
[3] C. W. Liu, M. H. Lee, C. F. Lin, I. C. Lin, W. T. Liu, and H. H. Lin, Tech. Dig. Int. Electron Devices Meet. 749 (1999).
[4] C. W. Liu, M. H. Lee, M.-J. Chen, I. C. Lin, and C.-F. Lin, Appl. Phys. Lett. **76**, 1516 (2000).
[5] A. St. Amour and J. C. Sturm, Tech. Dig. Int. Electron Devices Meet. 769 (1995).
[6] J. C. Sturm, A. St. Amour, Q. Mi, Lori C. Lenchyshyn, and M. L. W. Thewalt, Jpn. J. Appl. Phys., Part 1 **33**, 2329 (1994).
[7] X. Xiao, C. W. Liu, J. C. Sturm, L. C. Lenchyshyn, and M. L. Thewalt, Appl. Phys. Lett. **60**, 1720 (1992).
[8] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), p. 15.
[9] Y. Taur and T. H. Ning, *Fundamentals of Modern VLSI Devices* (Cambridge University Press, New York, 1998), p. 300.
[10] A. St. Amour, Ph.D. thesis, Princeton University (1996).