APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 3 15 JANUARY 2001

Reduced temperature dependence of luminescence from silicon due to field-induced carrier confinement

Ching-Fuh Lin,[a),b)] Miin-Jang Chen,[b)] Eih-Zhe Liang,[b)] W. T. Liu, and C. W. Liu
Department of Electrical Engineering, National Taiwan University Taipei, Taiwan, People's Republic of China

(Received 7 August 2000; accepted for publication 10 November 2000)

Electroluminescence from metal–oxide–semiconductor structures on Si was experimentally found to be much less temperature dependent than photoluminescence of Si. The physical reason is attributed to the field-induced carrier confinement in a small region, which contains much less impurity states, compared to the unconfined region. Thus, electron–hole recombination by radiation emission instead of through highly temperature-dependent impurity states is increased. A proposed model well explains the reduced temperature dependence with the field-induced carrier confinement. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1339842]

Si is the most important material for electronics due to the mature technology of integrated circuit fabrication on Si. Unfortunately, its difficulty of light emission as a result of indirect-band gap characteristics makes it much less useful for optoelectronics. Therefore, many efforts had been attempted to overcome the indirect-band gap obstacle. Those efforts include porous-silicon-based devices,[1,2] nanocrystalline Si,[3,4] Si^+-implanted SiO_2,[5] Er-doped Si,[6] and so on. We had also recently discovered electroluminescence (EL) from metal–oxide–semiconductor (MOS) on Si.[7] Different from other reports on EL of Si,[8,9] the EL in our experiments corresponds well with the band gap energy of Si. Phonon-assisted radiative recombination of electrons and holes could explain such luminescence well and the emission spectrum could also be well fitted by the model of electron–hole plasma for a wide temperature range.[10,11] From the model of electron–hole plasma, it appears that the EL and photoluminescence (PL) involve very similar mechanisms except the way of excitation. In this letter, we will report the difference of temperature dependence between EL and PL and explain the reason for the difference. Such a difference may give one a hint for enhancing luminescence efficiency on Si.

The investigation is made on the comparison of PL on Si and EL from the MOS structure. The MOS structure has a very thin oxide for significant current to tunnel through. The ultrathin gate oxide was grown by the RTO at 900 °C with the gas flows of 500 sccm nitrogen and 500 sccm oxygen at the pressure of 500 mbar. Aluminum metal pads were then immediately deposited by evaporation on the oxide. Figures 1(a) and 1(b) show EL and PL spectra at different temperatures, respectively. In the experiments, the heat generation causes the spectra to correspond to a temperature higher than the sample holder. The temperatures indicated in Figs. 1(a) and 1(b) are estimated by the theoretical fit to the measured spectra using the electron–hole plasma model. Although the temperature-dependent electron–hole plasma model explains the EL spectra well, the much less temperature dependence of EL, compared to the PL, remains unexplained.

In the MOS structure, EL occurs near the Si/SiO_2 interface,[7] where either electrons or holes tunnel from the metal side for MOS, depending on the MOS on p-Si or n-Si substrate. One argument may say that the tunneling effect is insignificantly dependent on temperature, so EL is less temperature dependent. However, for PL, carriers are generated by laser illumination. The amount of photo-excited carriers is not temperature dependent either. Therefore, the difference of temperature dependence for EL and PL should not be due

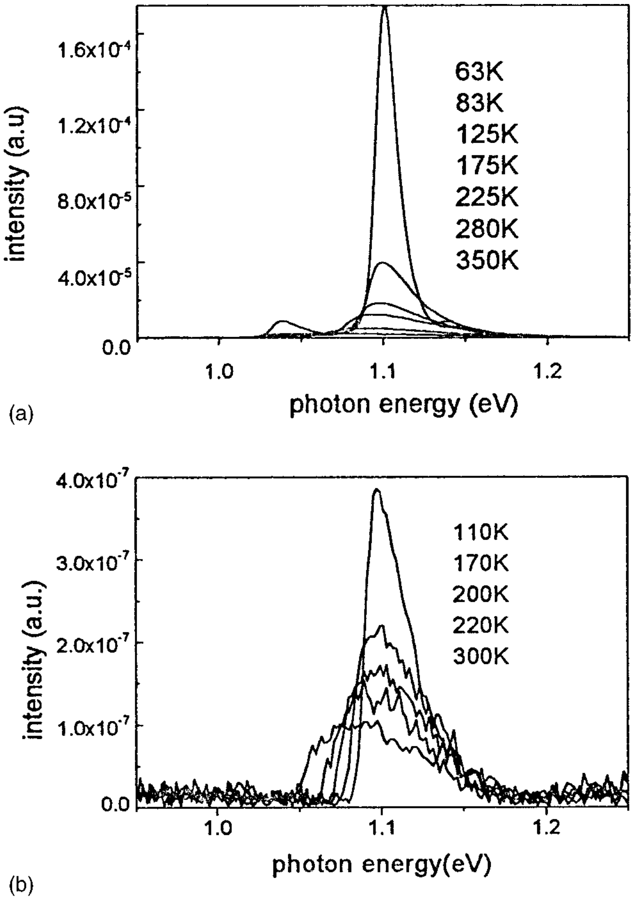

FIG. 1. (a) PL spectra at different temperatures and (b) EL spectra at different temperatures.

[a)] Electronic mail: cflin@cc.ee.ntu.edu.tw

[b)] Also at Graduate Institute of Electro-Optical Engineering, National Taiwan University Taipei, Taiwan, People's Republic of China.

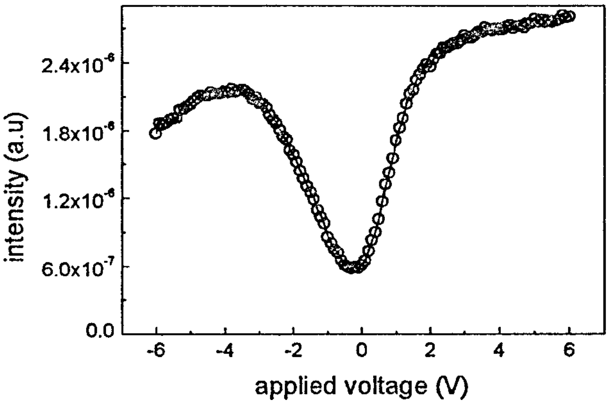

FIG. 2. Intensity of PL vs applied voltage.

to the way of carriers being generated. The field applied in MOS structure could be most likely the reason. To further confirm such an argument, PL is also measured from the MOS structure on *p*-Si with the gate metal replaced with transparent indium tin oxide. When the MOS has no bias, the PL measurement is similar to the case of bulk Si. As the MOS is under bias, the PL intensity significantly increases. Figure 2 shows the variation of PL intensity with the biased voltage for MOS on *p*-Si. Because the PL was measured only at the chopped frequency of illuminated laser light, the measured PL intensity did not contain the possible EL when the sample is under dc forward bias.

Several important features are revealed by such measurement shown in Fig. 2. First, luminescence is increased no matter when the sample is under forward or reversed bias. The PL intensity increases more than five times for the gate voltage increases from 0 to 4 V. Second, for reversed bias, PL remains low for a range of ~0.8 V. In this range, the Fermi level of Si is in the band gap and far from both the conduction band and the valence band, leading to less accumulation of carriers at the Si/SiO$_2$ interface. Thus, radiative recombination is reduced. Third, when the device is under extremely reversed bias, the PL drops again because the strong field rapidly sweeps the carriers out of the interface before they recombine. Forth, under forward bias, the PL eventually saturates because almost all of the photo-excited carriers are accumulated near the interface for sufficiently large voltage. When MOS is under either forward or reversed bias, band bending leads to the formation of a potential well at the Si/SiO$_2$ interface. This results in the confinement of electrons or holes in a thin sheet of region. Therefore, the accumulation of carriers in a small region is critical for enhanced luminescence no matter the carriers are photo excited or injected through tunneling.

According to this discussion, a simple model is proposed to explain the reduced temperature dependence of EL when the electric field is applied to the MOS structure so that carriers are confined in a small region. As excess electrons, more than thermal equilibrium, are generated either by photo excitation or tunneling effect, they could transit to valence band through radiative recombination or impurity states. Figures 3(a) and 3(b) schematically shows the situations with and without the carrier confinement, respectively.

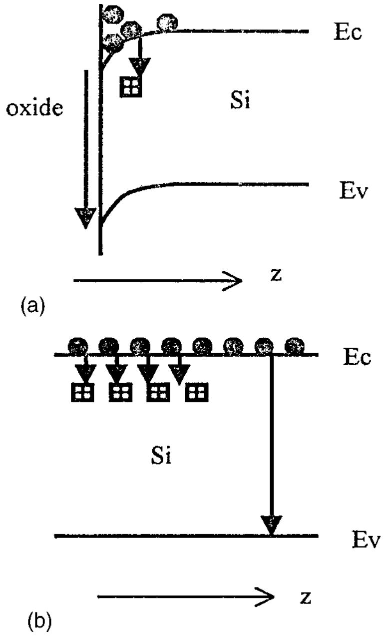

FIG. 3. Schematic for the effect of potential well and carrier confinement on electron–hole recombination: (a) with (b) without carrier confinement. (Ec: conduction band; Ev: valence band.)

Because the excess electrons will eventually transit to the valence band, the total amount of excess electrons (n_{ex}) is the sum of those radiatively recombined with holes (n_r) and those transiting through impurity states (n_i), as described by the following equation:

$$n_{\text{ex}} = n_r + n_i . \tag{1}$$

This equation is also valid for excess holes because a pair of an electron and a hole is generated or annihilated simultaneously. Because radiative recombination occurs for the annihilation of an electron and a hole, the strength of band-edge emission is proportional to the product of the numbers of excess electrons and holes, n_r^2.

The impurity states that could serve for electron transition to valence band are those ionized atoms, so their number depends on temperature according to $\exp(-Ei/kT)$, where Ei is the energy difference between the impurity level and the conduction-band edge. Therefore n_i is proportional to $\exp(-Ei/kT)$. If there is no carrier confinement, as shown in Fig. 3(b), many ionized atoms in a very large volume could be used for electron transition to valence band. At a very large temperature, their numbers are numerous, so almost all of the excess electrons transit to valence band through them. At low temperatures, very few ionized atoms exist, so the excess carriers could mostly recombine radiatively. Thus, the temperature dependence of the number of radiatively recombined carriers can be expressed as

$$n_r = n_{\text{ex}}(1 - e^{-Ei/kT}). \tag{2}$$

On the other hand, with carrier confinement [Fig. 3(a)], only a limited amount of ionized atoms in the region of carrier confinement could be used for electron transition to valence band. Then, the maximum n_i is only a portion of n_{ex}. Therefore,

$$n_r = n_{\text{ex}}(1 - \gamma e^{-Ei/kT}), \tag{3}$$

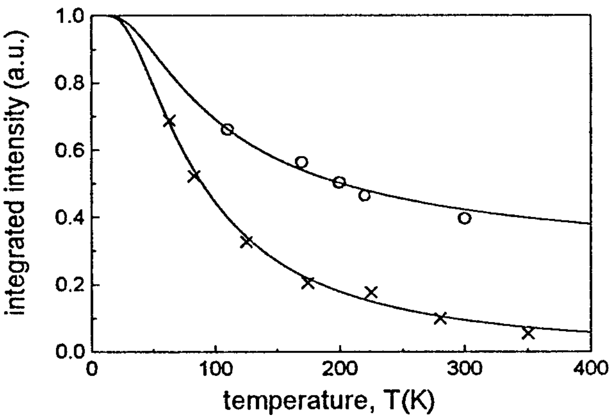

FIG. 4. Temperature dependence of EL and PL. (○: EL experiment; *x*: PL experiment; solid line: theoretical prediction.)

where $\gamma = n_i / n_{\mathrm{ex}} < 1$. The normalized band-edge emission then has the following temperature dependence

$$I = (1 - e^{-Ei/kT})^2 \tag{4}$$

for the case of no carrier confinement and

$$I = (1 - \gamma e^{-Ei/kT})^2 \tag{5}$$

for the case of carrier confinement. The theoretical prediction of temperature dependence with $Ei = 9.46\,\mathrm{meV}$ and $\gamma = 0.505$ is plotted in Fig. 4 for both cases. Figure 4 also shows the experimental temperature dependence of the total strength of luminescence integrated over the wavelength taken from Figs. 1(a) and 1(b). For EL, the normalized luminescence strength decreases to about 0.5 when the temperature varies from 10 to 300 K. In comparison, the normalized PL luminescence drops to less than 0.1 for temperature increasing from 10 to 300 K. Both theoretical curves fit the experimental results pretty well.

The fitting parameter $\gamma < 1$ indicates that less ionized atoms in EL are involved in the electron transition than in PL. Therefore, the carrier confinement near the Si/SiO_2 interface due to the applied field well explains the reduced temperature dependence. $Ei = 9.46\,\mathrm{meV}$ indicates that shallow levels are involved in the electron transition. Although deep levels are better irradiative recombination centers,[12] the indirect-band gap characteristics should make the rate of electron–hole radiative recombination very small and lead to the possibility of electron transition through the shallow levels. On the other hand, exciton radiative transitions may occur in Si for temperatures up to 1000 K.[13] In this case, *Ei* means the energy difference between the impurity level and the exciton level, while the exciton level is about 15 meV below the conduction-band edge.[14]

In conclusion, EL of MOS on Si was experimentally found to be much less temperature dependent than PL of Si. The reason is attributed to the field-induced potential well that causes the carrier confinement in a thin region. A simple model is proposed to explain the reduced temperature dependence as a result of the field-induced carrier confinement. From this model, the number of electrons transiting to valence band through highly temperature-dependent impurity states is reduced because of carrier confinement. Thus electron–hole recombination by radiation emission instead of through impurity states is increased. The temperature dependence is well explained by this model.

This work is supported in part by National Science Council, Taipei, Taiwan, R.O.C. under Contract No. NSC89-2215-E-002-016, NSC89-2112-M-002-034, and 88-2218-E-002-004.

[1] L. T. Canham, Appl. Phys. Lett. **57**, 1046 (1990).
[2] S. Lazarouk, P. Jaguiro, S. Katsouba, G. Masini, S. La Monica, G. Maiello, and F. Ferrari, Appl. Phys. Lett. **68**, 2108 (1996).
[3] S. Schuppler, S. L. Friedman, M. A. Marcus, D. L. Adler, Y.-H. Xie, F. M. Ross, Y. J. Chabal, T. D. Harris, L. E. Brus, W. L. Brown, E. E. Chaban, P. F. Szajowski, S. B. Christman, and P. H. Citrin, Phys. Rev. B **52**, 4910 (1995).
[4] D. B. Geohegan, A. A. Puretzky, G. Duscher, and S. J. Pennycook, Appl. Phys. Lett. **73**, 438 (1998).
[5] L. S. Liao, X.-M. Bao, X.-Q. Zheng, N.-S. Li, and N.-B. Min, Appl. Phys. Lett. **68**, 850 (1996).
[6] M. Matsuoka and S. Tohno, Appl. Phys. Lett. **71**, 96 (1997).
[7] C.-F. Lin, C. W. Liu, M.-J. Chen, M. H. Lee, and I. C. Lin, J. Appl. Phys. **87**, 8793 (2000).
[8] Y. Q. Wang, T. P. Zhao, J. Liu, and G. G. Qin, Appl. Phys. Lett. **74**, 3815 (1999).
[9] J. Yuan and D. Haneman, J. Appl. Phys. **86**, 2358 (1999).
[10] C. W. Liu, M. H. Lee, M.-J. Chen, I. C. Lin, and C.-F. Lin, Appl. Phys. Lett. **76**, 1516 (2000).
[11] C. W. Liu, M.-J. Chen, I. C. Lin, M. H. Lee, and C.-F. Lin, Appl. Phys. Lett. (unpublished).
[12] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).
[13] V. Alex, S. Finkbeiner, and J. Weber, J. Appl. Phys. **79**, 6943 (1996).
[14] D. E. Kane and R. W. Swanson, J. Appl. Phys. **73**, 1193 (1993).