APPLIED PHYSICS LETTERS **86**, 223502 (2005)

Electroluminescence from metal/oxide/strained-Si tunneling diodes

M. H. Liao
Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

M.-J. Chen
Department of Material Science and Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

T. C. Chen and P.-L. Wang
Department of Electrical Engineering and Graduate Institute of Electronic Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

C. W. Liu[a]
Department of Electrical Engineering, Graduate Institute of Electro-Optical Engineering, and Graduate Institute of Electronic Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

(Received 20 October 2004; accepted 14 April 2005; published online 24 May 2005)

The metal-oxide-silicon light-emitting diode under biaxial tensile mechanical strain is studied. The emission line shape of the device can be fitted by the electron-hole-plasma recombination model. The energy gap of strained Si extracted by the light emission spectra at the temperature of 120 K is reduced by 15 meV under 0.13% biaxial tensile strain. The light intensity of the device under 0.13% biaxial tensile strain increases 9% as compared to the relaxed-Si device. The upshift of valence band edge under mechanical strain to increase the majority hole concentration at the oxide/Si interface may be responsible for this light emission enhancement. The mechanical strain is measured by Raman spectroscopy, strain gauge, and analyzed by the finite element method. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1937989]

Strained Si attracts a great attention recently due to the enhancement of carrier mobility. The substrate strain technology using the lattice misfit between Si and SiGe can yield global biaxial strain,[1,2] but the high cost and high defect density make the substrate strain technology difficult for production. The biaxial strain also suffers the small hole mobility enhancement at high field.[3] The process-induced strain[4] and package strain[5] can give the strain large enough for mobility enhancement with the low cost. The process-induced strain technology has been used in the 90 nm technology node. The strain in Si not only changes the carrier mobility but also changes the band gap and band edges due to the deformation potential.[6,7] The band-gap shrinkage of Ge under the tensile strain was reported recently[8,9] based on absorption measurement which probes relatively thick sample. No luminescence results are reported for strained Si or Ge. In this letter, we report the electroluminescence (EL) from strained-Si using metal-oxide-silicon (MOS) tunneling diode. The radiative recombination of the electron-hole plasma at the accumulation layer of MOS diode can probe the band-gap reduction of Si under strain. Note that the EL is originated at the very thin accumulation layer on the order of nanometer, and can probe the local strain effect, while photoluminescence (PL) is originated from the bulk Si and probes the average strain effect within the absorption length of excitation wavelength on the order of micrometer.

The 3 nm oxide used in the MOS tunneling diode is grown by liquid phase deposition (LPD) at 60 °C on 12 mm × 12 mm *p*-type wafer with the resistance of 1–5 Ω cm. Due to the traps in LPD oxide, the trap-assistant electron tunneling is significant even with 3 nm LPD oxide. At negative bias, the electrons tunnel from the Al gate to *p*-type silicon, and the holes also tunnel from *p*-type silicon to Al gate. However, due to the different barrier heights between electrons (~3.1 eV) and holes (~4.6 eV), the hole current is smaller than the electron current. Meanwhile, the negative gate bias also attracts holes in the silicon/oxide interface and the electrons can recombine with holes to possibly emit light at the accumulation layer. The thickness is measured by ellipsometry. The *n*-type MOS (NMOS) diodes have Al gate electrodes with the circular area defined by the shadow mask. Another Al contact is on the back of the wafer.

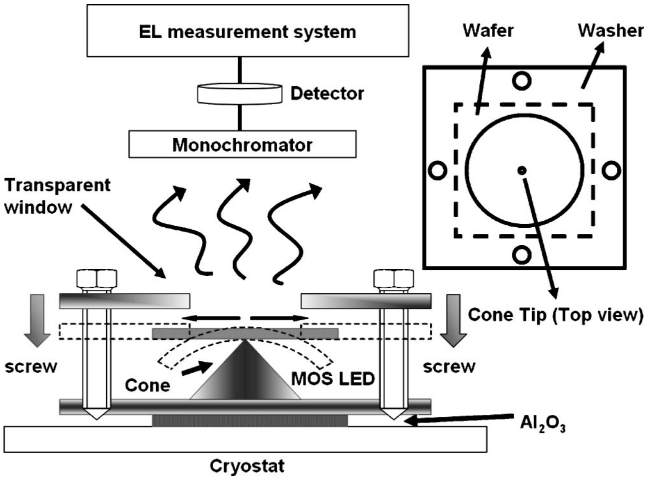

FIG. 1. Schematic diagram of the mechanical setup to apply strain in the low temperature cryostat.

---

[a] Author to whom correspondence should be addressed; electronic mail: chee@cc.ee.ntu.edu.tw

0003-6951/2005/86(22)/223502/3/$22.50

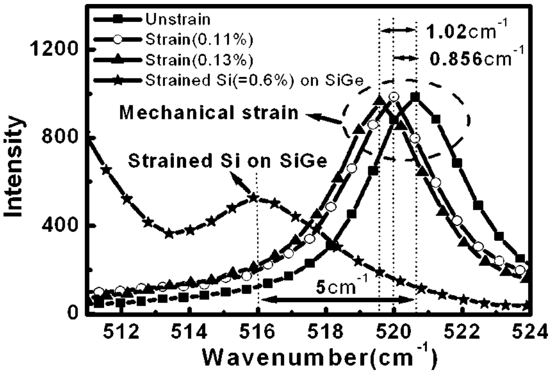

FIG. 2. Raman spectra of the mechanical strained Si. The position of Si–Si peak of strained Si indicates 0.11%, and 0.13% biaxial tensile strain. Strained Si on $Si_{0.8}Ge_{0.2}$ buffer is also shown for reference.

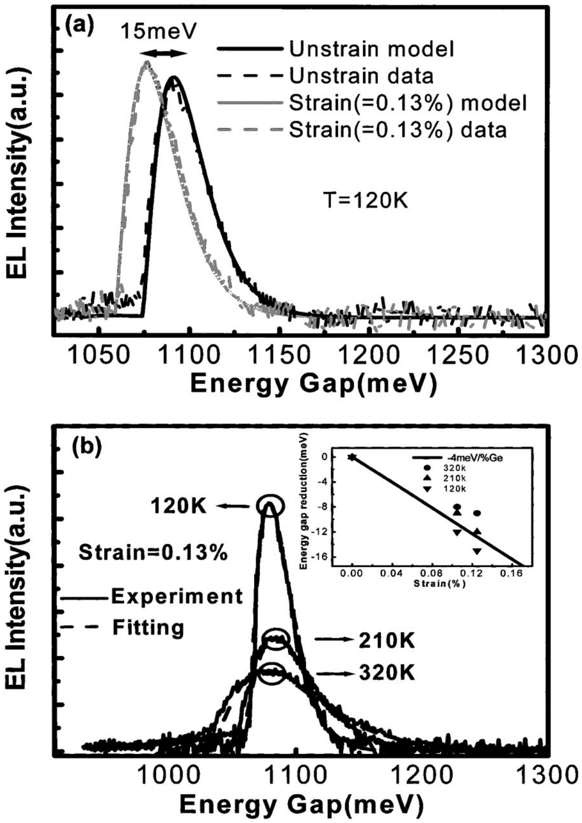

FIG. 4. (a) Measured electroluminescence spectra of relaxed/strained MOS LED with the fitting curves of the electron-hole plasma recombination model; (b) EL spectra of strained MOS LED (0.13% strain measured by Raman spectroscopy) at 120, 210, and 320 K. The inset of (b) shows the theoretical curve (−4 meV/%Ge strain) and the band-gap reduction data from EL.

The experimental setup of mechanism for EL measurement is schematically shown in Fig. 1. The MOS light-emitting diode (LED) on 12 mm × 12 mm *p*-type wafer sits on the tip of a cone. Then, the sample is clamped by a 20 mm × 20 mm square washer with an inner hole of 10 mm in diameter. The level of strain is determined by the four screws on each side of the square washer. The strain of the Si under mechanical strain is simulated by finite element method (ANSYS), and measured by the Raman spectroscopy and strain gauge. The whole mechanism is made of copper to dissipate the heat from the electrical power. The high thermal conductivity of copper makes the temperature of MOS LED close to the cryostat temperature. Note that the whole copper mechanism has the dimension of 20 mm × 20 mm × 7 mm, small enough to insert into the chamber of the cryostat.

Raman spectra is excited by the laser with the wavelength of 514 nm, which has a absorption length of 540 nm in Si. The Si–Si peak of silicon in the Raman spectra (Fig. 2) shifts towards the negative axis under the external biaxial tensile strain. The Raman shift of 0.856 and 1.02 cm^{-1} under biaxial tensile strain were extracted from the curve fitting using Lorentzian profile, corresponding to the biaxial strain of 0.11% and 0.13%, respectively.[10] The strain level obtained from Raman shift agrees well with the ANSYS simulation, and has a small deviation from strain gauge measurement (Fig. 3). The strain gauge measures the strain of a relatively large area (2 mm × 1 mm) on the strained Si surface. The shift of Si–Si peak for strained Si (strain = 0.6%) on SiGe is also shown for reference.

Figure 4(a) shows the EL spectra at 120 K from the unstrained/strained MOS LED samples with the device size of 4×10^{-2} cm^2. The current used to drive the device is the periodical pulse with the period of 30 ms and 17% duty cycle to reduce the Joule heating. The on current of the pulse is 200 mA. The electron-hole plasma recombination model is used to fit the EL spectra.[11,12] The band gap and device temperature are obtained from the fitting of the EL spectra. The energy gap extracted by the light emission spectra at the temperature of 120 K from the relaxed device is reduced by 15 meV under 0.13% biaxial tensile strain measured by Raman spectroscopy. Figure 4(b) shows the EL spectra of strained MOS LED at 120, 210, and 320 K. It is found that the EL spectrum is broadened with the increasing temperature due to the wide distribution in energy of electrons and holes at high temperature. The theoretical curve and experimental data of Si band-gap reduction as a function of strain are also shown in the inset of Fig. 4(b). The strain in Fig. 4(b) is measured by Raman shift. It shows that the Si band gap is reduced under the biaxial tensile strain. The theoretical value of ΔE_g due to strain is calculated to be −4 meV/Ge% strain,[13] which is close to the experimental result. Figure 5 shows integral light emission intensity as a function of biaxial tensile strain at 300 K. Under the 0.13% biaxial tensile strain, the light intensity from MOS LED increases 9%. It could be due to the increase of majority hole concentration at oxide/silicon interface, since the large hole concentration increases the radiative recombination rate of electrons and holes. The upshift of valence band edge to increase the hole tunneling barrier may be the origin to increase hole concentration at Si/oxide interface. Using different parameters in Refs. 14–16 with the formula in Ref. 7, and the data in Refs.

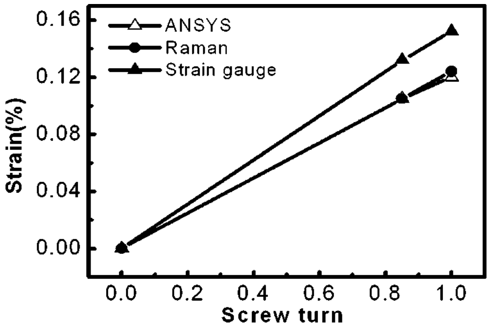

FIG. 3. Strain measured by Raman, strain gauge and simulated by ANSYS as a function of the number of screw turn.

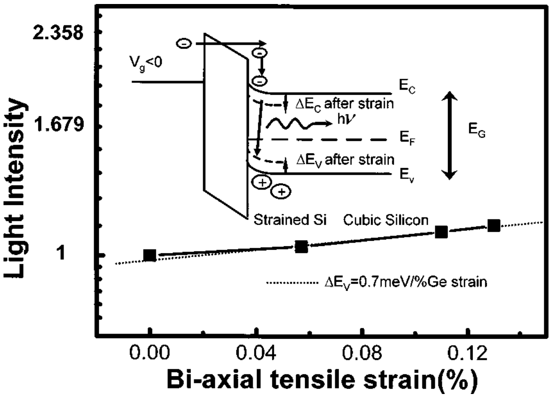

FIG. 5. Integrated EL emission intensity vs biaxial tensile strain at 300 K. The inset shows the energy band diagram of MOS LED on *p*-type Si wafer at the accumulation bias. The dashed line and solid line represent the band edges of the unstrained and strained device, respectively.

17,18 the shift of valence band edge due to strain can vary from −0.8 meV/%Ge strain to +4.5 meV/%Ge strain, where "−" sign and "+" sign indicate the downshift and upshift of valence band edge, respectively, and 1% Ge strain equals 0.0417% strain. The band diagram of Al/$\mathrm{SiO_2}$/*p*-type Si at the accumulation condition is shown in the inset of Fig. 5. The strained LED has larger hole tunneling barriers to decrease the hole tunneling rate into the Al electrode, and more holes are accumulated at the oxide/Si interface. With the assumption of the hole concentration increase by a factor of $e^{\Delta E_V/KT}$ due to the increase of the tunneling barrier ΔE_V, the ΔE_V can be obtained by fitting the intensity versus strain curve, and the upshift of +0.7 meV/%Ge is obtained. In our model, the hole concentration in the accumulation layer is responsible for electron-hole recombination. The doping in the Si neutral region has no effect for the recombination. As a result, the upshift of valence band edge under biaxial tensile strain increases the hole concentration at accumulation layer, and light emission intensity increases.

In summary, the EL from strained Si can be used to measure the band-gap reduction due to the strain. Since electron-hole plasma recombination occurs at the thin accumulation layer (several nanometer from the interface), the local strain can be measured with the known band-gap reduction as a function of strain, which is approximately −4 meV/%Ge strain. The increase of the integral emission intensity with increasing strain suggests that the valence band edge of Si shifts upwards and the hole tunneling barrier increases.

The support of Raman measurement by Professor Chih-Ta Chia at the National Taiwan Normal University is highly appreciated. This work is supported by National Science Council of ROC under Contract Nos. 93-2215-E-002-003 and 93-2215-E-002-017.

[1] J. J. Welser, J. L. Hoyt, and J. F. Gibbons, IEEE Electron Device Lett. **15**, 100 (1994).

[2] M. H. Lee, P. S. Chen, W.-C. Hua, C.-Y. Yu, Y. T. Tseng, S. Maikap, Y. M. Hsu, C. W. Liu, S. C. Lu, W.-Y. Hsieh, and M.-J. Tsai, Tech. Dig., Int. Electron Device Meeting, 69 (2003)

[3] J. L. Hoyt, *Symposium of 206th ECS Conference: SiGe: Materials, Processing, and Devices* (2004), 15.

[4] D. Giles, M. Armstrong, C. Auth, S. M. Cea, T. Ghani, T. Hoffmann, R. Kotlyar, P. Matagne, K. Mistry, R. Nagisetty, B. Obradovic, R. Shaheed, L. Shifren, M. Stettler, S. Tyagi, X. Wang, C. Weber, and K. Zawadzki, Symp. VLSI Tech. Dig, 118 (2004).

[5] S. Maikap, M. H. Liao, F. Yuan, M. H. Lee, C. F. Huang, S. T. Chang, and C. W. Liu, Tech. Dig., Int. Electron Device Meeting, (2004), p. 233.

[6] C. Tserbak, H. M. Polatoglou, and G. Theodorou, Phys. Rev. B **47**, 7104 (1993).

[7] C. G. Van de Walle, Phys. Rev. B **34**, 5621 (1986).

[8] Y. Ishikawa, K. Wada, D. D. Cannon, J. Liu, H. C. Luan, and L. C. Kimerling, Appl. Phys. Lett. **82**, 2044 (2003).

[9] J. Liu, D. D. Cannon, K. Wada, Y. Ishikawa, S. Jongthammanurak, D. T. Danielson, J. Michel, and L. C. Kimerling, Appl. Phys. Lett. **84**, 660 (2004).

[10] J. C. Tsang, P. M. Mooney, F. Dacol, and J. O. Chu, J. Appl. Phys. **75**, 8098 (1994).

[11] X. Xiao, C. W. Liu, J. C. Stum, L. C. Lenchyshyn, and M. L. W. Thewalt, Appl. Phys. Lett. **60**, 1720 (1992).

[12] C. W. Liu, M.-J. Chen, I. C. Lin, M. H. Lee, and C.-F. Lin, Appl. Phys. Lett. **77**, 1111 (2000).

[13] R. People, IEEE J. Quantum Electron. **22**, 1696 (1986)

[14] EMIS Datareviews Series No. 20, *Properties of Crystalline Silicon*, edited by R. Hull (1999), p. 404.

[15] C. G. Van der Walle, Phys. Rev. B **39**, 1871 (1989).

[16] M. V. Fischetti and S. E. Laux, J. Appl. Phys. **80**, 2234 (1996).

[17] J. J. Welser, Ph.D. thesis, Standford University, 1994.

[18] S. E. Thompson, G. Sun, K. Wu, J. Lim, and T. Nishida, Tech. Dig. - Int. Electron Devices Meet., (2004), p. 221.