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Strong Stark effect of electroluminescence in thin SOI MOSFETs

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1. Introduction

Silicon-based optoelectronics are now attracting much attention because of the ability to integrate optical functionality and high-speed interconnections into silicon chips. Light emission in nanometer-scale Si has been widely studied over the past few decades because the quantum confinement in such a system is expected to enhance the light emission efficiency due to the increased dipole matrix elements and the quantum confined excitonic effects [1, 2]. Experimental investigations cover a variety of systems such as porous silicon [3], quantum dots [4], and quantum wells based on silicon-on-insulator (SOI) technology [5]. As described in recent electroluminescence (EL) studies [6], the Si quantum well (QW) system based on SOI MOSFETs is a promising candidate due to its compatibility with CMOS and efficient carrier-injection capability. However, the effect of quantum confinement and the gate electric field on the emission spectra and efficiency have not yet been clarified.

Here we report the electroluminescence from thin SOI MOSFETs when electrons are injected into a thin SOI layer by tunneling. We observed a large Stark shift of up to approximately 50 meV by applying an electric field normal to the thin SOI layer. The observed strong Stark effect indicates that strong quantum confinement in the Si/SiO$_2$ system plays an important role in light emission.

2. Device Structures

The devices were SOI MOSFETs with an n-type polycrystalline Si (poly-Si) tunneling gate (Fig. 1(a)), which were similar to those used in previous studies on tunneling spectroscopy of electron subbands in the SOI channel [7]. Two channel thicknesses (t_{SOI}), 8.5 and 25 nm, were investigated. The thicker Si contact regions are implanted with either P or B to form contacts to the electrons or holes, respectively. The thicknesses of the front gate oxide (t_{FOX}), and the buried oxide (t_{BOX}) were approximately 2 and 400 nm, respectively. A cross sectional transmission electron microscope (TEM) image and the band profile of the device are respectively shown in Figs. 1(b) and 1(c).

3. Experimental Results and Discussion

The EL spectra were measured at 80 K with a grating monochromator and cooled InGaAs array detector. For carrier injections, we applied negative front gate voltage (V_{FG}) while all the n$^+$ and p$^+$ contacts were grounded. Thus, electrons are injected from the gate into the thin SOI channel, while holes are injected into the channel from the p+ contact. In order to investigate the Stark effect, we changed the back gate voltage (V_{BG}), which can vary the electric field normal to the SOI channel.

Figs. 2(a) and 2(b) show typical V_{FG} dependence of the EL spectra at V_{BG} = 0 V for the device with t_{SOI} = 25 and 8.5 nm, respectively. The main effect of V_{FG} is to change the injection current. The integrated EL intensities normalized by the front gate area as a function of tunneling current $|I_{LG}|$ are shown in Fig. 3. For t_{SOI} = 25 nm, three dominant peaks appear at A1: 0.988, A2: 1.048, and A3: 1.088 eV. While five peaks at B1: 0.988, B2: 1.047, B3: 1.078, B4: 1.108, and B5: 1.134 eV are observed for t_{SOI} = 8.5 nm. The origins of the peaks are not clear at present, but we speculate from their energies that A3, B3, and B4 are related to electron-hole plasma/liquid or free excitons. We attribute A2 and B2 to impurities because the SOI channel is likely phosphorous doped by phosphorous atoms diffused from the n+ poly-Si gate through tunnel oxide during thermal processes in the device fabrication. The EL intensities show sublinear dependence on the injection current, which may reflect the effect of non-radiative Auger recombination. It is difficult to know the exact carrier density, but it is estimated to be in the order of 10^{18} cm^{-3} at $|I_{LG}|$ = 40 μA if we assume that the radiative recombination lifetime is 1 μs.

Fig. 4(a) shows the V_{BG} dependence of the EL spectrum for the device with t_{SOI} = 25 nm. For $V_{BG} < 0$, the dependence is rather low because the holes are distributed over the whole channel due to the negative V_{FG} and V_{BG}, and thus the electric field across the SOI channel is low. For $V_{BG} > 0$, holes are pushed towards the FOX/SOI interface and electrons are attracted to the BOX/SOI interface. Then, carriers are widely separated so that the EL intensity rapidly decreases as the peak energies show a small red shift (~3 meV). On the other hand, the V_{BG} dependence of the EL spectrum for t_{SOI} = 8.5 nm exhibited a much larger red-shift up to 50 meV as shown in Fig. 4(b). The large shift results from the strong Stark effect in the Si/SiO$_2$ QW. In this thinner QW, the confinement is strong enough for the wavefuncitons of electrons, and holes still overlap even under a larger electric field. In Fig. 5, the integrated EL intensities normalized by $|I_{LG}|$ as a function of V_{BG} are compared. The figure clearly shows that the EL efficiency for t_{SOI} = 8.5 nm is higher than that for t_{SOI} = 25 nm. These differences in the Stark shift and the EL efficiency indicate that the EL originates from the SOI channel. Furthermore, the quantum confinement plays an important role in luminescence.

In order to analyze the Stark shift more quantitatively, we calculated the electric field dependence of the transition energy and the overlap integral of the envelope functions between the electron and hole ground states in the SiO$_2$/Si/SiO$_2$ QW. In Fig. 6, the calculated overlap integral as a function of the Stark shift is shown with the experimental results. The figure shows that the rapid decrease in the intensity for t_{SOI} = 25 nm is well reproduced in the calculation. On the other hand, for t_{SOI} = 8.5 nm, the experimental intensity remains high and deviates from the calculation up to the Stark shift around 40 meV. Then it suddenly approaches the calculated value as the Stark shift approaches close to 50 meV. Thus, the Stark shift of 50 meV agrees quite well with the theoretical prediction; the corresponding electric field is 150 kV/cm. The observed abrupt change suggests that the electron-hole pair is localized at first and then dissociates into a quantum confined state of the QW in a large electric field. For t_{SOI} = 25 nm, an e-h pair can easily become dissociated because the transition energy of the QW states becomes lower than that for the localized state in a smaller electric field. It should be noted that a similar tendency was obtained for ionization of a donor atom close to the SiO$_2$/Si interface [8].

4. Conclusions

We observed EL in thin SOI MOSFETs when electrons are injected from the gate by tunneling. Prominent Stark effects appeared due to the strong confinement in the Si/SiO$_2$ QW. The present results demonstrate that it is important to control the quantum confinement and the gate electric field to achieve light emitting devices based on SOI MOSFETs.

Acknowledgement

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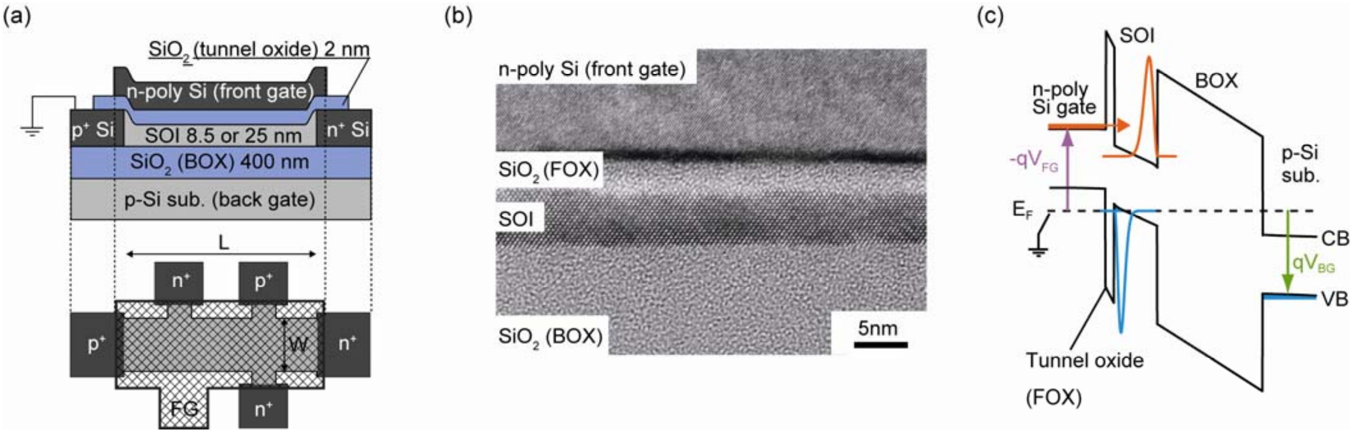

Fig. 1. (a) Schematic diagram of a cross section of the device. The tunneling poly-Si gate defines the channel with width (*W*) and length (*L*). (b) Cross sectional transmission electron microscope image of the device with t_{SOI} = 8.5 nm. (c) Band diagram of the device.

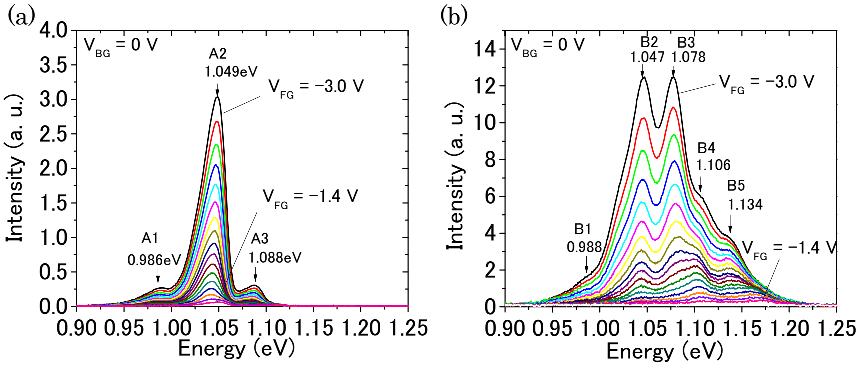

Fig. 2. V_{FG} dependence of EL at V_{BG} = 0 V in the device with (a) t_{SOI} = 25 nm and L x W = 200 x 30 μm, and (b) t_{SOI} = 8.5 nm and L x W = 50 x 30 μm.

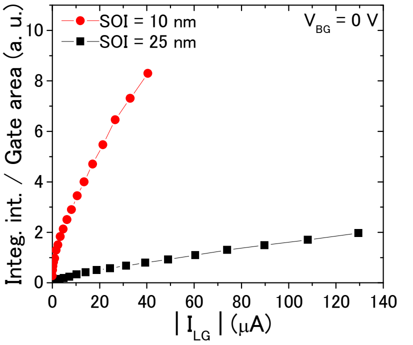

Fig. 3. Integrated EL intensity normalized by gate area as a function of tunneling current $|I_{LG}|$ at V_{BG} = 0 V.

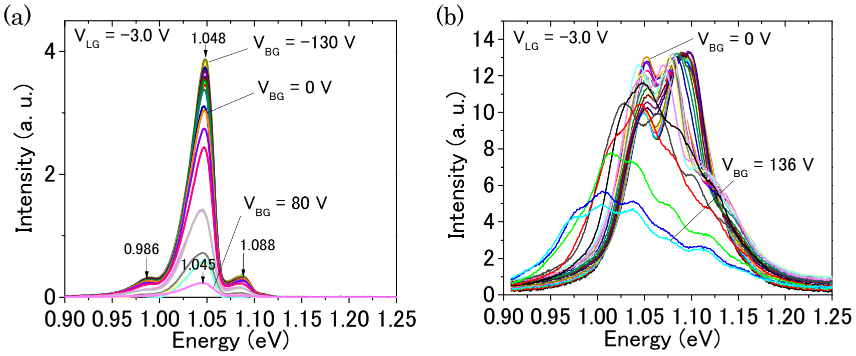

Fig. 4. V_{BG} dependence of EL at V_{FG} = -3.0 V in the device with (a) t_{SOI} = 25 nm and L x W = 200 x 30 μm, and (b) t_{SOI} = 8.5 nm and L x W = 50 x 30 μm.

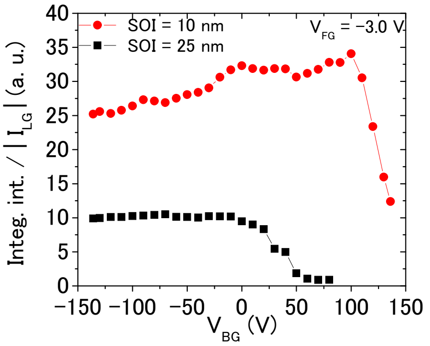

Fig. 5. The EL intensity normalized by $|I_{LG}|$ as a function of V_{BG} at V_{FG} = -3.0V.

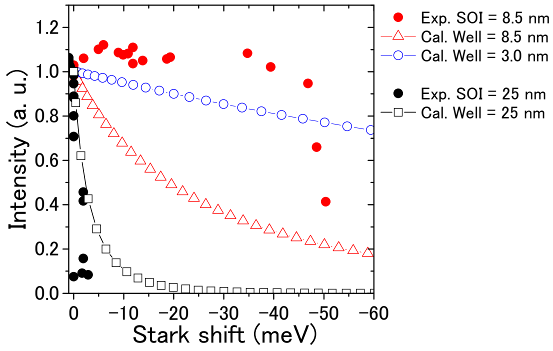

Fig. 6. Comparison between the experimental EL intensity and calculated overlap integral for QWs as a function of the Stark shift for the device with t_{SOI} = 8.5 and 25 nm. In order to see the effect of carrier localization, we also plotted the calculation of the well width of 3 nm.