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LETTER TO THE EDITOR

## Infrared electroluminescence from metal-oxide–semiconductor structures on silicon

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**Abstract.** Room temperature electroluminescence from metal-oxide–semiconductor structures on silicon is observed. The thin oxide is grown by rapid thermal oxidation. With the metal negatively biased, luminescence can be observed. The emission is voltage dependent. For an applied voltage below 5 V, the emission occurs around 1150 nm, approximately corresponding to the Si bandgap energy. For a larger applied voltage, the emission shifts to wavelengths much longer than 1150 nm. The physical reason for the electroluminescence at bandgap energy is attributed to disorder near the Si–SiO<sub>2</sub> interface, while the electroluminescence at longer wavelengths could be possibly caused by the c–c or v–v radiative transition.

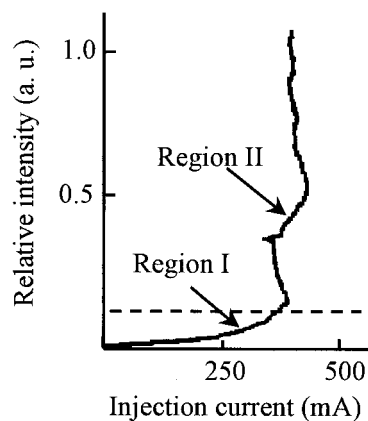
Silicon is the most important semiconductor material for the integrated-circuit (IC) industry. However, its importance in optoelectronics is not as prominent due to its indirect bandgap characteristics. For decades, many efforts have been devoted to making silicon useful for optics or optoelectronics. These efforts include fabricating optical waveguides [1] or micro-optics [2] on Si, as well as converting silicon into light-emitting materials such as porous-silicon-based devices [3–5], nanocrystalline Si [6, 7], Si<sup>+</sup>-implanted SiO<sub>2</sub> [8, 9], and so on. Recently, visible electroluminescence (EL) has also been reported from Ag/SiO<sub>2</sub>/Si structures or similar metal-oxide–semiconductor (MOS) structures with native oxide [10, 11]. Such structures provide a simple method of generating light from Si. However, the native oxide usually contains deficient defects and its EL property strongly relies on the forming environment [12]. In this work, we report that EL is also observed from MOS structures on Si with the oxide grown by well controlled rapid thermal oxidation (RTO). The emission corresponds to the bandgap energy and to longer wavelengths, the physical reasons for which will be discussed. Such MOS structures with RTO grown oxide are particularly advantageous as compared to other types of luminescent structure on Si because their processing steps are completely compatible with IC fabrication.

The MOS structure that emits luminescence is almost the same as conventional structures [13]. The oxide is only 2.3 nm thick, which is thin enough for significant current to tunnel through. This ultra thin gate oxide was grown by RTO at 900 °C. The gas flows were 500 sccm nitrogen and 500 sccm oxygen at a pressure of 500 mbar. The thickness was measured using ellipsometry and confirmed by x-ray reflectivity. The resistivity of the 100 mm p-type wafers used in this study was 1–5 Ω cm<sup>-1</sup>. Aluminium metal pads were then immediately

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deposited on the oxide by evaporation. The metal pads were comprised of circular areas of different diameters and cross lines with width 0.1 mm.

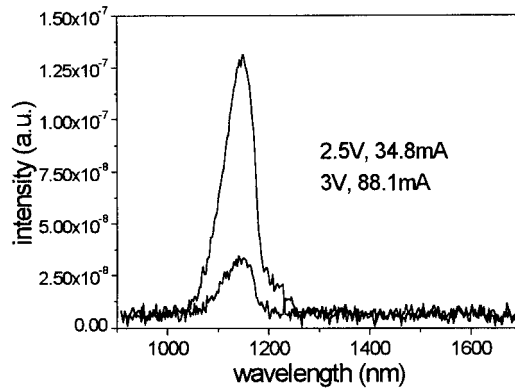
When a voltage, negative with respect to the p-type substrate, was applied to the metal pads, a significant current was measured. In the meantime, luminescence was clearly observed through an IR-viewer even with a current density as low as  $0.67 \text{ A cm}^{-2}$ . Because the metal pads were made of thick aluminium, the luminescence was observed to mainly emit from the periphery of the circular area, similar to a total eclipse of sun. Therefore, only a small portion of light was measured. The output power should significantly increase if the Al metal pads were replaced with transparent electrodes. On the other hand, with the metal being positively biased even up to a few volts, only a very small amount of current could flow through the thin oxide, showing fair rectification characteristics. No luminescence was observed for the positively biased metal.



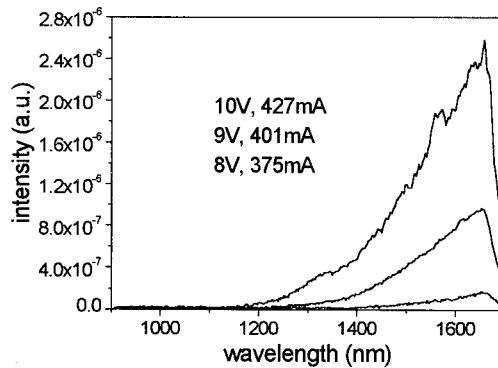
**Figure 1.** The  $L-I$  characteristics of the electro luminescence from the MOS on p-type silicon. Region I: below dashed line metal is negatively biased below 5 V; region II: above dashed line is negatively biased above 5 V.

The output power was measured using an InGaAs detector under cw operation without cooling. Figure 1 shows the measured  $L-I$  curve, which consists of two obviously different parts, regions I and II, corresponding to the applied voltage approximately below and above 5 V, respectively. For region I, the curve shows a superlinear increase of the output power with the injection current. In region II, abnormal  $L-I$  characteristics are observed.

The EL spectra for different current levels and applied voltages were measured using a monochromator for the sample under cw operation without cooling. Figure 2 shows the measured spectra for the light output in region I of the  $L-I$  curve. The emission occurs around 1150 nm, which corresponds to the bandgap energy,  $E_g$ , of Si slightly above room temperature. By increasing the applied voltage, the emission power initially increases with the injection current, but then gradually decreases as the voltage approaches 5 V. When the applied voltage increases beyond 5 V, the luminescence near 1150 nm completely vanishes and then luminescence at longer wavelengths appears. The measured spectra are shown in figure 3 at different applied voltages. These spectra correspond to the abnormal characteristics of region II in the  $L-I$  curve. As shown in figure 3, when the applied voltage further increases, the spectra move towards shorter wavelengths, though the wavelengths remain longer than 1150 nm. The measured spectra are limited by the InGaAs detector. The entire spectra should extend beyond 1700 nm.



**Figure 2.** The measured spectra for MOS on p-type silicon under cw operation without cooling for region I of figure 1.

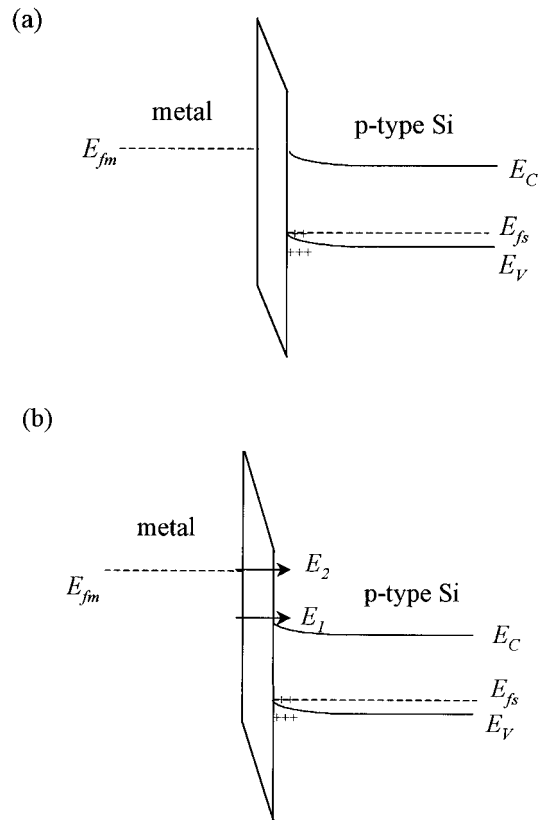


**Figure 3.** The measured spectra for MOS on p-type silicon under cw operation without cooling for region II of figure 1.

In contrast to earlier reports [10, 11, 14] no visible luminescence was measured from our devices. The emission is only in the IR regime beyond 1000 nm. In addition, our luminescence was observed only when the devices were forward biased. Also, the emission around 1150 nm has a superlinear increase of light output with injection current, which is different from the report in [11]. The above differences might be due to the different mechanisms involved.

The visible luminescence from MOS with native oxide has been explained before [14, 15] as being due to luminescent centres or oxygen deficient defects in the native oxide. In our devices, because the oxide was grown by well controlled RTO, it should have much fewer defects than the native oxide. Thus the disappearance of the visible luminescence is reasonable.

The physical reasons for the EL around 1150 nm could be explained as follows. When the metal is negatively biased, its Fermi level ( $E_{fm}$ ) moves up. As it approaches the conduction band edge ( $E_c$ ) tunnelling current increases significantly because many states in the conduction band suddenly appear. The sudden increase of current causes the applied voltage to drop mostly across the resistance part in the substrate, so  $E_{fm}$  changes very slightly. Meanwhile, the negative bias of metal causes the band of the p-type silicon to bend up near the Si-SiO<sub>2</sub> interface, as schematically shown in figure 4(a), leading to the formation of a potential



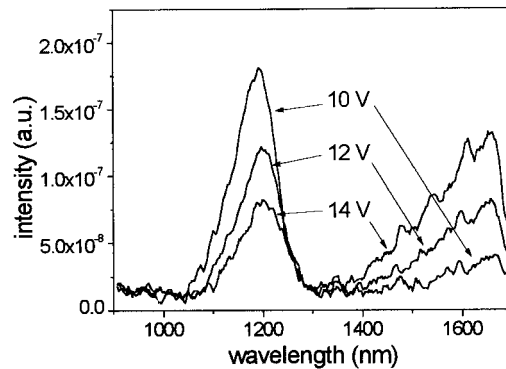
**Figure 4.** A schematic of the band diagram with the metal of the MOS structure negatively biased: (a)  $E_{fm}$  near  $E_c$ ; (b)  $E_{fm}$  far above  $E_c$ .

well for hole confinement. Consequently, large populations of holes and tunnelling electrons simultaneously appear near this interface. In addition, the lattice disorder near the Si–SiO<sub>2</sub> interface probably relaxes the requirement of momentum conservation [16]. Both factors greatly increase the probability of radiative recombination.

The emission energy corresponding to 1150 nm is slightly less than the Si bandgap energy at the room temperature for the following reasons. Firstly, the sample is heated up under a large injection current, so the bandgap energy is reduced. Secondly, the bandgap shrinkage with the increasing carrier density [17] might also result in red shift. And thirdly, the interruption of the Si periodical structure at the interface causes band bending and bandgap shrinkage [13].

When the applied voltage increases to beyond 5 V,  $E_{fm}$  moves far above  $E_c$ , as schematically shown in figure 4(b). Then electrons with energy  $E_1$  near  $E_c$  see an increased potential barrier, so their tunnelling probability is reduced. On the other hand, the total tunnelling current still increases because the electrons with their energy  $E_2$  near  $E_{fm}$  have increased their tunnelling probability as a result of the strongly tilted potential barrier. Those electrons then tunnel into the high energy states of the conduction band. Therefore, radiative recombination corresponding to  $E_g$  is reduced.

The reasons for emission at longer wavelengths for the voltage above 5 V are discussed as follows. Firstly, it might be due to the interfacial states in the grown oxide. However, the  $C$ – $V$



**Figure 5.** Shift of emission spectrum from 1200 nm to beyond 1300 nm with increasing applied voltages for MOS on n-type Si.

measurement indicates only a very small amount of interface trap in the oxide, implying that the interfacial states are probably not significant. In addition, the spectrum is voltage dependent, so the interfacial states are not likely to be the main cause. Secondly, black body radiation might also be the reason. To identify if the emission is caused by black body radiation, similar measurements have been performed with the sample cooled. Under the same bias condition, the emission near 1600 nm for the sample cooled down to 10 K is even stronger than at 300 K, indicating that black body radiation alone could not explain the emission well. Thirdly, as  $E_{fm}$  moves up further, as shown in figure 4(b), electrons tunnel to the states far above  $E_c$ . These hot carriers could then relax to lower energy states, e.g.  $E_2 \rightarrow E_1$ , by direct or phonon-assisted inter-conduction band radiation [18, 19]. Similar behaviour was observed for MOS on n-type Si, on which emission occurs around  $E_g$  for metal positively biased at the low voltage and shifts to longer wavelengths for large bias voltages. Figure 5 shows the gradual shift of spectrum from 1200 nm to beyond 1300 nm with increasing applied voltages for MOS on n-type Si. This observation illustrates the possibility of the third mechanism. As discussed before, at large applied voltages the number of tunnelled carriers with energy near the band edge is reduced, while more carriers tunnel into the high energy states. Therefore, emission corresponding to  $E_g$  is reduced and the probability of direct or phonon-assisted c-c or v-v radiation increases.

In conclusion, room temperature EL from the simple MOS structure on silicon with the thin oxide grown by the well controlled RTO is observed. For the applied voltage below 5 V, the EL wavelength is around 1150 nm, which approximately corresponds to the Si bandgap energy. When the applied voltage is increased to beyond 5V, the emission wavelength becomes longer than 1150 nm and voltage dependent.

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