Novel electroluminescence from Metal-Insulator-Semiconductor (MIS) structures on Si

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Abstract - Room temperature electroluminescence from metal-insulator-semiconductor (MIS) structures on Si was observed. Several types of MIS structures such as Al/SiO$_2$/Si, ITO/SiO$_2$/Si, and mechanically pressed ITO/Si contact, has been investigated. Both band-edge and visible electroluminescence are observed from the ITO/SiO$_2$/Si structures. The devices based on the Al/SiO$_2$/Si structure exhibit efficient band-edge electroluminescence. Electroluminescence near the silicon bandgap energy is also achieved from MIS structures using an innovative mechanically pressed ITO/Si contact. Optical phonons, interface roughness, localized carriers and impact ionization are used to explain radiative recombination in MIS structures.

A. Introduction

It is an important goal to integrate Si ULSI circuits with optoelectronics in order to improve the speed limitation of electrical interconnects. Many techniques such as Si/SiGe alloy, porous-silicon, nanocrystalline Si, and Er-doped Si, have been developed to overcome the poor luminescent property of Si [1]. However, this luminescence originates from defect-related mechanisms and the fabrication processes are complex. Recently, we have observed electroluminescence (EL) from Al/SiO$_2$/Si MIS tunneling diodes [2]. The structure of MIS tunneling diode is the same as that used in ULSI circuits and the fabrication process is fully compatible with present ULSI techniques. Consequently, light-emitting MIS tunneling diodes show promise as practical on-chip light sources for optical interconnection and silicon-based optoelectronics integrated circuits (OEIC). In this study, we present several MIS structures for EL on Si.

B. ITO/SiO$_2$/Si structure

In this work, the ultrathin gate oxide in the ITO/SiO$_2$/Si MIS structure was grown by the rapid thermal oxidation (RTO) to allow sufficient tunneling current for radiative recombination. The ITO gate metal was deposited by sputtering. The ITO/SiO$_2$/Si MIS structure on p-type Si has both visible and band-edge EL, while the ITO/SiO$_2$/Si MIS on n-type Si structure has only band-edge emission [3]. Figs. 1 (a) and (b) show the band-edge EL and visible EL spectra of ITO/SiO$_2$/Si on p-type Si, respectively. The band-edge EL of ITO/SiO$_2$/Si on n-type Si is similar to Fig. 1(a). The difference is due to the impact ionization that only occurs for ITO/SiO$_2$/Si MOS on p-type Si. The impact ionization is caused by the ballistic electrons tunneling from the ITO gate to the Si. As schematically shown in Fig. 2, some of the tunneling hot electrons recombine with holes radiatively. Because of the high kinetic energy of the hot electrons, the emission wavelength is larger than the bandgap energy and the spectrum is broad. Impact ionization also reduces the band-edge EL. Fig. 3 shows the relative intensities of visible and band-edge EL vs. the applied voltage. The intensity is normalized to each

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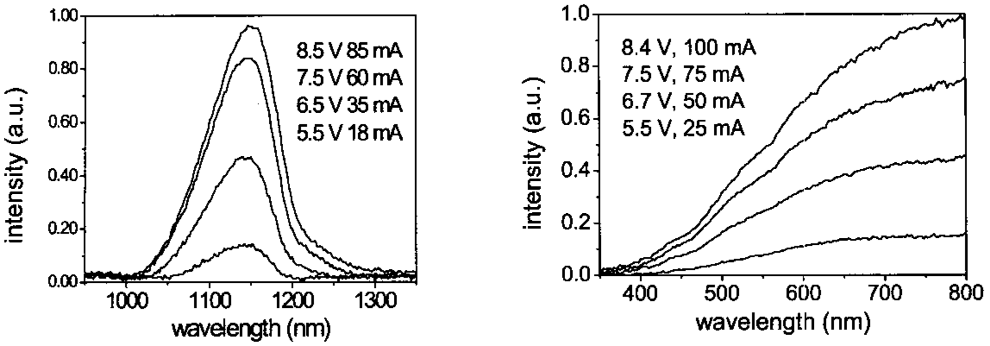
measured value at 10V of visible EL and band-edge EL, respectively. The competition between band-edge EL and visible EL is clearly demonstrated.



(a) (b)

Fig. 1 (a) Band-edge EL and (b) visible EL spectra of ITO/SiO_2/Si on p-type Si

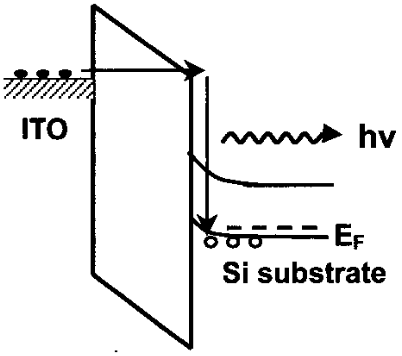


Fig.2. Schematic diagram for visible EL due to impact ionization

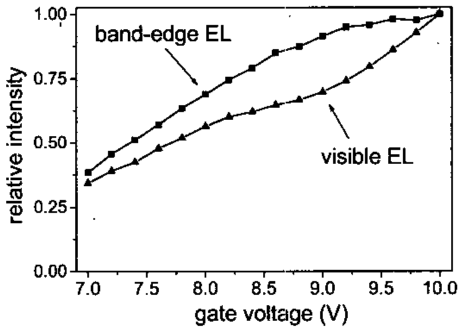


Fig.3. The relative intensity of visible EL and band-edge EL vs. the applied voltage.

C. Al/SiO2/Si structure

Band-edge EL is also observed from MIS structures with RTO grown oxide and an Al metal gate deposited by evaporation. The band-edge EL spectrum is similar to Fig. 1(a). Fig. 4 shows the efficient luminescence versus current (L-I) curve for an Al/SiO_2/Si MIS structure on n-type Si.

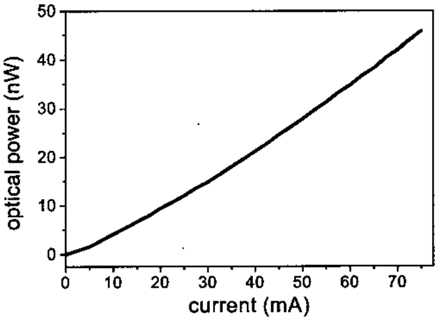


Fig. 4 L-I curve for Al/SiO_2/Si on n-type Si

Since the luminescence was blocked by the thick Al gate electrode, only emission from the gate electrode edge could be measured. However, the estimated EL efficiency of the original EL near the Si/SiO_2 interface be of the order of 10^{-5}. To further study the luminescent properties of the MIS tunneling diodes, the dependence of EL and photoluminescence (PL) was investigated. The dependence of band-edge EL is also discovered to be much less than the PL from Si. Fig. 5 shows the temperature dependence of EL and PL. The experiment demonstrates that the EL intensity of MIS tunneling diodes has a weak temperature dependence as compared to PL. The reason is attributed to carrier confinement in the accumulation layer, which is related to the gate voltage and is almost independent of temperature. In addition, carriers confined in a small region are captured by fewer impurity states, resulting in a reduced temperature dependence.

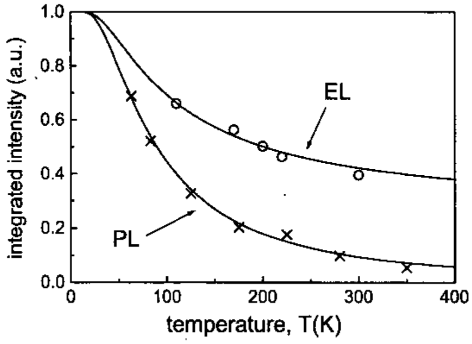


Fig.5 Temperature dependence of EL and PL
(o, x: experimental results; solid line: theoretical prediction.)

The measured shape of the EL and PL spectra are very similar. This resemblance indicates TO phonon participation in the radiative recombination of the MIS silicon tunneling diodes.

D. Mechanically pressed ITO/Si contact

Room-temperature EL corresponding to the Si bandgap energy was also observed from mechanically pressed ITO/Si contact. The experimental setup is shown schematically in Fig.6. A piece of glass with indium tin oxide (ITO) was used as the base to support the structure and the native oxide on the Si surface was removed by buffer-oxide-etchant . On the top of the Si substrate, pressure was applied by a micrometer. The EL spectra are similar to Fig.1(a).

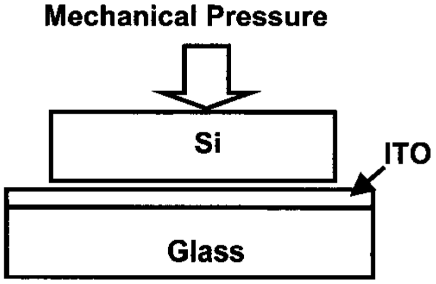


Fig.6 Schematic setup of the mechanically pressed ITO/Si contact

Fig.7 shows that the intensity of luminescence is pressure-dependent. Under constant forward-bias current, the EL intensity decreases with pressure and eventually vanishes. The physical reason for the EL at low pressure is attributed to the formation of an air gap between the ITO and Si substrate, similar to the EL from an MIS structure. Under very large pressure, the ITO directly contacts Si everywhere so that no carriers accumulate near the insulator/Si interface, and EL disappears. This study indicates that the formation of an air gap between the ITO surface and Si substrate is crucial for EL.

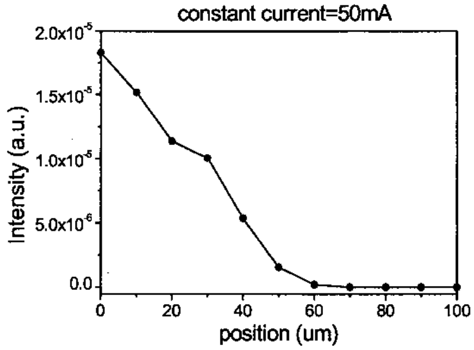


Fig.7 The EL emission strength vs. micrometer reading (applied pressure)

E. Discussion and Conclusion

Possible reasons for the occurrence of EL from the MOS silicon tunneling diodes at room temperature are discussed as follows. Because of the indirect bandgap nature of Si, extra mechanisms are required for momentum conservation during radiative recombination. In addition to the participation of phonons, the carrier scattering by Si/SiO$_2$ interface roughness is shown to be important to provide some momentum to compensate the momentum-mismatch between the electrons and holes in the k-space [4]. Therefore, more phonons with momentum complementary to the interface roughness scattering are involved in the radiative recombination with the existence of the roughness. In addition, localized majority carriers in the accumulation region will result in a spread of momentum in k-space and provide a similar function to that of the interface roughness. The spreading of the wavefunction in k-space due to interface roughness and localized carriers could enhance EL for Si.

In summary, several MIS structures on Si were studied for electroluminescence. The insulator in a MIS structure could be either an SiO$_2$ layer, grown by rapid thermal oxidation, or an air gap formed by mechanically pressed ITO/Si contact. The EL from the mechanically pressed ITO/Si contact shows that the insulator of the MIS structure is very important for EL on Si. For metal/oxide/Si(p) structures, both band-edge EL and visible EL are observed, and the visible EL is attributed to impact ionization.

References

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