Light Emission Near 1.3 μm Using ITO–Al_2O_3–$Si_{0.3}Ge_{0.7}$–Si Tunnel Diodes

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***Abstract*—We have fabricated $Sn:In_2O_3$ (ITO)–Al_2O_3 dielectric on $Si_{1-x}Ge_x$–Si metal–oxide–semiconductor tunnel diodes which emit light at around 1.3 μm, for $x = 0.7$. The emitted photon energy is smaller than the bandgap energy of Si, thus, avoiding strong light absorption by the Si substrate. The optical device structure is compatible with that of a metal–oxide–semiconductor field-effect transistor, since a conventional doped poly-Si gate electrode will be transparent to the emitted light. Increasing the Ge composition from 0.3 to 0.4 only slightly decreases the light-emitting efficiency.**

***Index Terms*—Al_2O_3, electroluminescence, light, light-emitting device (LED), SiGe.**

I. INTRODUCTION

THE BACKEND resistance–capacitance (*RC*) delay is one of the main challenges in very large scale integration (VLSI) technology. Advanced backend processes incorporating copper and low-K dielectrics, for instance, do not eliminate concerns about the ac power consumption and the *RC* delay in high performance circuits. Optical interconnects have been proposed and are considered to be a potential option for replacing the conductor–dielectric system for global interconnects [1]. However, the lack of an Si-based light source is the main bottleneck for this technology, in part due to the indirect bandgap in Si. An Si-based light-emitting device (LED) would also enable interchip optical wireless communications as well and optical fiber dense wavelength-division-multiplexing applications [2]. Recently, metal–oxide–semiconductor (MOS) tunnel diodes [3]–[5] have been proposed as a possible candidate for Si-based LEDs, because of their good performance and inherit integration capability with metal–oxide–semiconductor field-effect transistors (MOSFETs) and current VLSI technology. We have previously shown that the use of a high-K gate dielectric [6], [7] in a MOS tunnel diode can improve the light emission efficiency and reliability due to the strong quantum confinement for providing additional momentum in indirect bandgap Si [5]. However, the emitted photon energy is larger than the energy bandgap of Si [3], [5], which makes absorption in the Si substrate an issue. To overcome this problem, we have developed an $Sn:In_2O_3$ (ITO)–Al_2O_3 dielectric on $Si_{1-x}Ge_x$–Si [8]–[14] tunnel diode which has its emitted photon energy below the bandgap energy of Si. Combined with the advantage of a high-K gate dielectric, the ITO–Al_2O_3–$Si_{0.3}Ge_{0.7}$ device, with light emission in the ~1.3-μm range, shows great potential for optical interconnects and wireless communications.

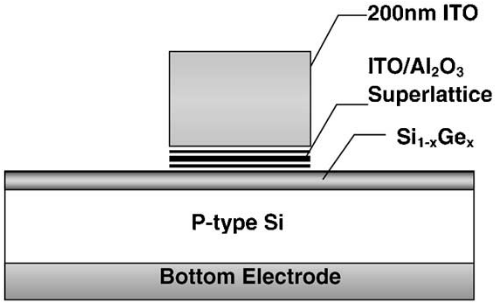

Fig. 1. Cross-sectional view of ITO–Al_2O_3–$Si_{0.3}Ge_{0.7}$ SL MOS tunnel diodes.

II. EXPERIMENTAL PROCEDURE

Standard 4-in (100) p-type Si substrates were used in this study. Layers of ~20-nm $Si_{0.3}Ge_{0.7}$ were formed on the Si wafers by solid phase-epitaxy (SPE), first depositing amorphous Ge on the native-oxide desorbed Si surface in a modified molecular beam epitaxy (MBE) system under high vacuum, followed by a rapid thermal annealing at 900 °C to form SiGe by SPE [8]. The advantage of SPE compared with ultrahigh vacuum chemical vapor deposition (UHVCVD) or direct MBE-grown SiGe is the high temperature stability, smooth surface, and high MOSFET device performance [8]–[14]. The low electrical defect in SPE-formed SiGe can also be evidenced from very small interface trap density close to Si [9]–[11]. Then, three periods of 2-nm ITO/1.5-nm Al_2O_3 superlattice (SL) gate dielectrics [5] were formed on the $Si_{0.3}Ge_{0.7}$. Top contacts were transparent ITO, 0.2 μm thick, which were subsequently sintered at 450 °C in N_2 ambient, to improve the ITO quality. For comparison, ITO–Al_2O_3–$Si_{1-x}Ge_x$ SL tunnel diodes with total 30-nm thickness and Ge compositions of 0.2 and 0.4 were also fabricated. Fig. 1 shows the cross-sectional view of fabricated device. The light emission was measured using a

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Manuscript received January 20, 2003; revised July 31, 2003. This work was supported by the NSC (92-2215-E-009-017).

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This work has been sponsored by the collaboration between National Science Council of Taiwan (NSC90-2215-E-009-052) and National Research Council of Canada.

Digital Object Identifier 10.1109/LPT.2003.818922

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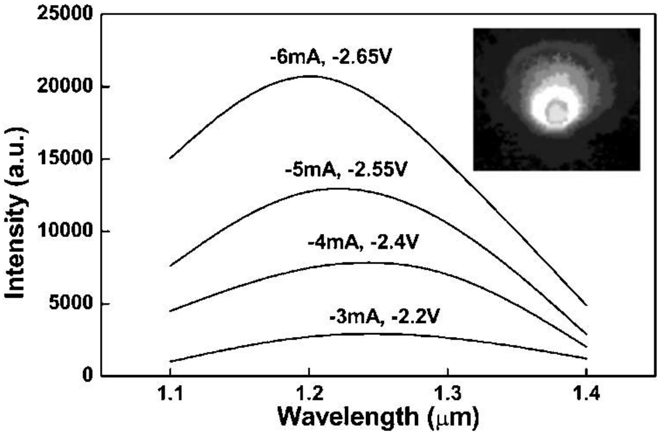


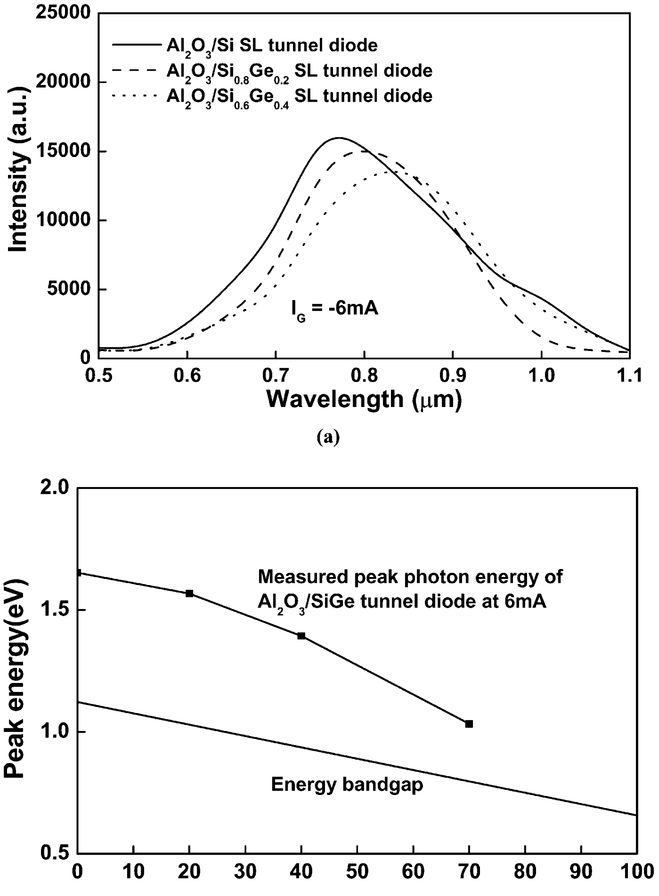
Fig. 2. Electroluminescence spectra of ITO–Al$_2$O$_3$–Si$_{0.3}$Ge$_{0.7}$ SL tunnel diodes with different injection current levels. The insertion figure is the picture of light emission at -6 mA.

Hamamatsu PHEMOS-1000 light detection system used in Si integrated circuit industry and equipped with charged-coupled device camera for infrared image. A conventional photomultiplier tube was used to detect the emitted at energies >1.1 eV, while an InGaAs detector was used at less than 1.1 eV.

III. RESULTS AND DISCUSSION

Fig. 2 shows the light emission spectra and light emission picture ($Ig = -6$ mA) of ITO–Al$_2$O$_3$–Si$_{0.3}$Ge$_{0.7}$ SL tunnel diodes. The image shows an uniform light emission from the tunnel diode with strong light emission. The emitted wavelength range, from 1.1 to 1.4 μm, covers the important wavelength of 1.3 μm used for optical fiber communication. The emitted photon energy increases with increasing gate voltage, which is similar to the Si MOS tunnel diode [5]. Since the emitted photon energy is less than the bandgap energy of Si, the optical loss through Si substrate absorption is reduced. Therefore, it would make such devices compatible with MOSFETs and they could be integrated into current VLSI.

To investigate whether the light emission originates from the SiGe quantum well, we have also measured the emission in ITO–Al$_2$O$_3$–Si$_{1-x}$Ge$_x$ tunnel diodes with different Ge compositions of 0, 0.2, and 0.4. Fig. 3(a) and (b) shows the variation of the measured spectra and peak photon energy with different Ge contents. The peak photon energy and spectra shift to lower energy with increasing Ge composition. This excludes the possibility that the electroluminescence is generated from the gate dielectric, because it is the same for all devices. The peak photon energy in MOS tunnel diode is always greater than the linear interpolated energy bandgap—this is consistent with our previous result [5]. The larger photon energy in MOS tunnel diode can be interpreted as due to hole quantization effect in the accumulation layer of the p-Si surface [14]. Due to hole quantization [15], the effective energy bandgap from conduction to valence band optical transition will be increased compared to the bulk SiGe energy bandgap. The energy increment becomes larger at higher gate voltage because of stronger hole quantum confinement, which is consistent with the peak energy blue shift data in Fig. 2. The strong confinement is the merit of high-K gate dielectric to achieve a small inversion layer thickness [5] and high current drive [6].



(a)

(b)

Fig. 3. Comparisons of (a) electroluminescence spectra and (b) the peak light emission energy of ITO–Al$_2$O$_3$–Si$_{1-x}$Ge$_x$ ($x = 0, 0.2$, and 0.4) SL tunnel diodes at -6-mA injection current.

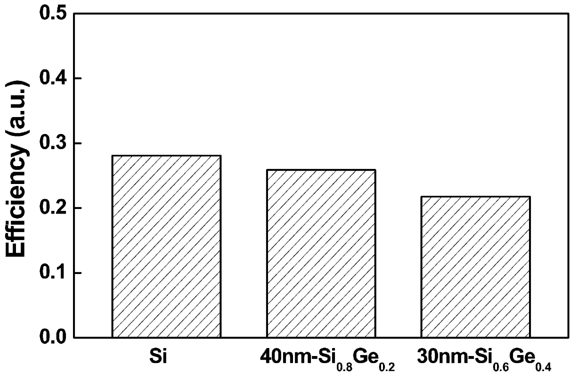


Fig. 4. Emission efficiency comparison for ITO–Al$_2$O$_3$–Si$_{1-x}$Ge$_x$ ($x = 0, 0.2$, and 0.4) SL tunnel diodes at -6-mA injection current.

Since the light emission efficiency is an important parameter for optical devices, we compare, in Fig. 4, this parameter for ITO–Al$_2$O$_3$–Si$_{1-x}$Ge$_x$ tunnel diodes with different Ge composition of 0, 0.2, and 0.4 under similar conditions with the same detection system. We can not compare this efficiency data with that of the ITO–Al_2O_3–$Si_{0.3}Ge_{0.7}$ devices because a different photodetector must be used. Although the luminescence efficiency decreases with increasing Ge concentration, the magnitude of the change, when the Ge composition is increased to 0.4, is not serious. This result is likely due to the excellent quality of the SiGe, which was deposited at the high epitaxy temperature of 900 °C. We note that in III–V semiconductors, high growth temperatures can improve the luminescence efficiency by more than one order of magnitude [16]–[18] and is the primary material epitaxy parameter for optical devices.

IV. CONCLUSION

We have fabricated ITO–Al_2O_3–$Si_{0.3}Ge_{0.7}$ MOS tunnel diodes and demonstrated emission $\sim 1.3\ \mu m$. The excellent optical properties, together with a device structure similar to that of MOSFET, suggest that these devices may enable the development of Si-based technology for optical interconnects and wireless communication.

ACKNOWLEDGMENT

The authors would like to thank Dr. L. H. Lai, Prof. H. C. Kou, and B. T. Chuang for the discussions and measurements assistance.

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