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# Efficient ultraviolet electroluminescence from a Gd-implanted silicon metal–oxide–semiconductor device

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Strong ultraviolet electroluminescence with an external quantum efficiency above 1% is observed from an indium-tin oxide/$SiO_2$:Gd/Si metal–oxide–semiconductor structure. The $SiO_2$:Gd active layer is prepared by thermal oxidation followed by $Gd^+$ implantation and annealing. The electroluminescence spectra show a sharp peak at 316 nm from the $^6P_{7/2}$ to $^8S_{7/2}$ transition of $Gd^{3+}$ ions. Micrometer-sized electroluminescent devices are demonstrated.

Light sources operating in the ultraviolet (UV) region are required for a number of applications, including solid-state lighting, biological agent detection, sterilization, and covert communication. Strong UV light emission from AlGaN-based emitters has been reported emitting in the UV range from 265 to 325 nm.[1–3] However, for the development of microlight sources for on-chip analysis, such as biochips, biosensors, microflorescent displays, etc., efficient silicon-based microlight sources are required which can be integrated into silicon integrated circuits. Silicon-based UV light emitters are promising for such applications. Recently, light emitters incorporating rare-earth $Er^{3+}$-, $Tm^{3+}$-, $Tb^{3+}$-, and $Ce^{3+}$-doped Si-rich $SiO_2$ have been reported with emission in the infrared to blue–green spectral regions.[4,5] Strong blue–violet emission at 390 nm has been reported in $Ge^{3+}$-implanted $SiO_2$ metal–oxide–semiconductor (MOS) structures.[6] Efficient silicon-based UV light emitters at a shorter wavelength from silicon device have not yet been reported for the time being. In this letter, we demonstrate a silicon–based efficient UV light emitter based on a $SiO_2$:Gd MOS structure delivering a sharp emission peak at 316 nm from $Gd^{3+}$ ions, which is comparable to the efficient UV emission of $ZnF_2$:Gd.[7] External quantum efficiencies above 1% are achieved with not fully optimized devices. Device sizes below 1 $\mu$m can be easily achieved with standard complementary MOS (CMOS) technology.

Electroluminescent (EL) devices are prepared by standard silicon CMOS technology on 4 in. *n*-type silicon wafer with resistivity of 2–5 Ω cm. The structure consists of an active gate oxide area surrounded by a field oxide (1 $\mu$m thick). The active layer is a 100 nm thick thermally grown $SiO_2$ layer implanted with $Gd^+$ ions at two energies of 50 and 110 keV with doses of $5\times10^{14}$ and $1\times10^{15}$ $cm^{-2}$, respectively. After annealing at 800 °C for 1 h, a plasma treatment was performed in a mixture of oxygen/hydrogen (90/10) for 5 min. The gate electrode consists of a 100 nm thick indium-tin oxide (ITO) deposited by rf sputtering. Various shapes of MOS structures with different feature sizes in the range of 1 to 500 $\mu$m were fabricated for testing the function of the EL devices dependent upon the geometry.

EL spectra were measured on a MOS structure with 500 $\mu$m diameter with a constant current supplied by a sourcemeter (Keithley 2410). EL signals were recorded at room temperature with a monochromator and a photomultiplier. The absolute EL power from the device was measured using a calibrated optical power meter. The external EL power efficiency is calculated by integrating the total EL output power from the front surface. Photoluminescence (PL) and photoluminescence excitation (PLE) spectra were also measured with the same system using UV excitation from a 75 W Xe lamp.

Figure 1 shows the PL and PLE spectra from the $SiO_2$:Gd gate oxide without an ITO electrode on top. The PL spectrum under the excitation of 195 nm UV light shows a sharp peak at 316 nm arising from the transition of $^6P_{7/2}$ to $^8S_{7/2}$ of the $Gd^{3+}$ ions.[8] The PLE spectrum of the 316 nm emission exhibits two excitation peaks at 195 and 274 nm. The peak at 195 nm corresponds to the excitation from $^8S_{7/2}$ to $^6G_{13/2}$ and the peak at 274 nm can be assigned to the $^8S_{7/2}$ to $^6I_J$ excitation of $Gd^{3+}$ (Ref. 9).

Figure 2 shows the EL spectra of the $SiO_2$:Gd at an injection current of 100 $\mu$A for the MOS structure with a

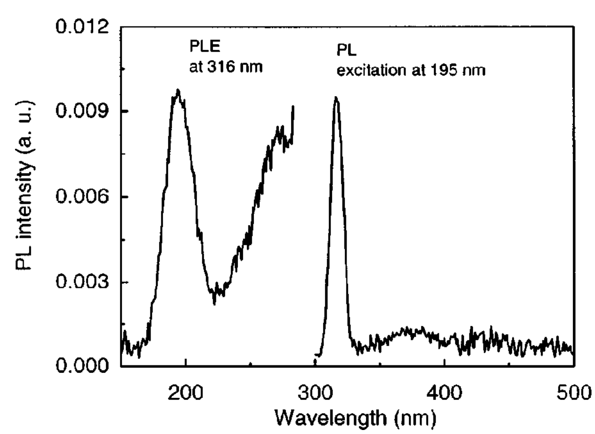


FIG. 1. PL and PLE spectra from the 100 nm $SiO_2$:Gd layer. The PL was excited by 195 nm UV light, and the PLE was measured with a detection wavelength of 316 nm.

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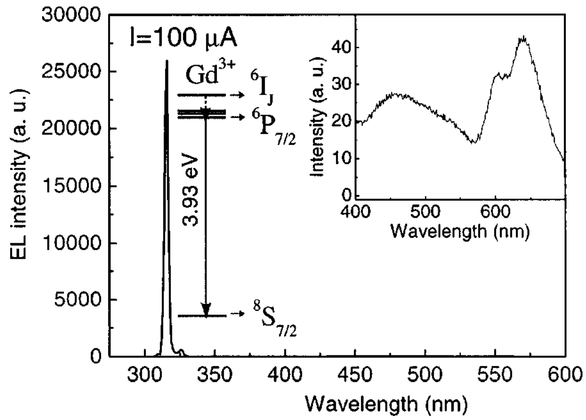


FIG. 2. EL spectrum of the $SiO_2$:Gd MOS device at 100 $\mu$A current and a sketch of the involved electronic transition. The inset shows the emission in the 400 nm to 700 nm region. Note that the intensity in this region is nearly three orders of magnitude lower than the emission at 316 nm.

diameter of 500 $\mu$m. The spectra show a strong peak at 316 nm from the transition of the lowest excited states of $^6P_{7/2}$ to $^8S_{7/2}$ from the $Gd^{3+}$ ions. Two broad peaks in the visible range centered at 460 nm and 650 nm are observed at higher current injection, as shown in the inset of Fig. 2. These bands have an intensity about three orders of magnitude lower than the 316 nm peak at the same injection current. The bands originate from neutral oxygen vacancies and nonbridging oxygen hole centers as typical network defects of the amorphous silicon dioxide created by the implantation process.[10,11]

In order to clarify the excitation process of the UV emission, we analyze the current–field characteristics of the device as shown in Fig. 3. The ratio of the injection current density and the square of the electric field, i.e., $J/E^2$, plotted versus the reciprocal of the electric field which allows us to verify Fowler–Nordheim (F–N) tunneling injection of hot electrons at $SiO_2$/Si interface in the MOS structure expressed as $J/E^2=A\exp(-B/E)$, $A$ and $B$ are constants.[12] This expression is valid in the range from 8.5 MV/cm to 10.3 MV/cm. The inset of Fig. 3 shows the EL intensity of the 316 nm peaks from $Gd^{3+}$ as a function of the injected current of the MOS device. An external quantum efficiency of 1% is obtained for this device (with a power efficiency of $4-6\times 10^{-4}$). The threshold electric field for detection of the UV is about 8.5 MV/cm, which is the same as the threshold electric field for F–N tunneling injection of the hot electrons into the conduction band of the $SiO_2$ for strong electric heating.

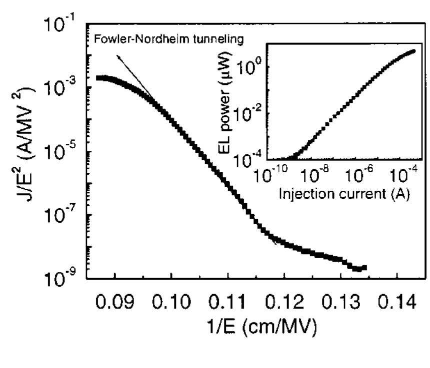


FIG. 3. The current density of the $SiO_2$:Gd MOS device divided by the squared electric field is plotted vs the reciprocal electric field (F–N plot of the current-field characteristic). The inset is the integrated EL power vs the injection current.

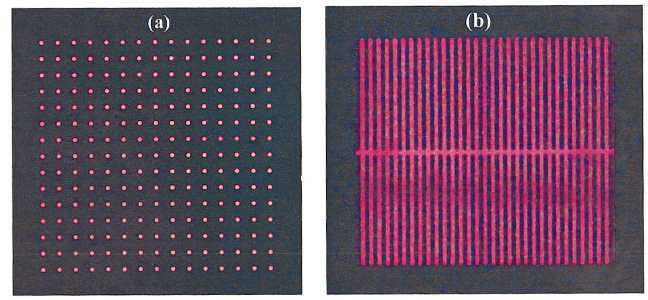


FIG. 4. (Color) CCD photograph of the EL from two different structures: (a) matrix of $15\times 15$ dots with a diameter of 20 $\mu$m and spacing of 70 $\mu$m and (b) comblike structure with an EL strip width of 4 $\mu$m. Note the observed visible light is 2000 times weaker than the UV peaks, which is not observed by the CCD camera.

According to the study of DiMaria *et al.*,[13] under such high electric fields of 8.5–11 MV/cm, as is necessary for the operation of our devices, the average hot electron energy is above 4 eV with respect to the bottom of the conduction-band edge of $SiO_2$; the average energy of the hot electrons is larger than the EL photon energy of 3.93 eV. Hence, a large number of hot electrons are capable of generating efficiently UV light from $Gd^{3+}$ by impact excitation in the $SiO_2$ host.

Figure 4 shows a matrix of $15\times 15$ devices of a 20 $\mu$m diameter MOS structure operated with a total injection current of 100 $\mu$A and a high-resolution comblike structure with EL strips of 4 $\mu$m width, both imaged with a Si charge coupled device (CCD) camera under an optical microscope. Note that only the visible part of the spectrum from the $SiO_2$ defect EL is observed, which is nearly three orders of magnitude weaker than the UV light. The smallest feature size is 2 $\mu$m which is limited by the capability of our lithography system. However, smaller sizes below 1 $\mu$m are possible for high-resolution display or biochip applications. Combination with red–green–blue phosphors, efficient silicon-based UV light emitters can be better candidates for the fabrication of high-resolution full-color microdisplays as compared to $ZnF_2$:Gd thin-film EL devices,[7] since the fabrication of silicon-based devices is fully compatible with standard MOS technology.

In summary, strong UV EL with an external quantum efficiency above 1% was reported from an ITO/$SiO_2$:Gd/Si MOS structure. The UV is generated by impact excitation of $Gd^{3+}$ ions by hot electrons. External quantum efficiencies above 1% were obtained at room temperature for further optimization by changing the oxide thickness and Gd concentration. EL devices on a micrometer-scale can be fabricated employing standard CMOS technology.

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