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Continuous reddish-yellow visible-light emission at room temperature in Mn-doped Si surface light-emitting diodes

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Silicon (Si) is the central material in modern electronics. Unfortunately, due to its *indirect* band-gap structure, Si does not emit light efficiently. As a result, photonic devices such as light-emitting diodes (LEDs) or lasers commonly use III-V semiconductor materials with direct band-gap structures. However, since the chemical and physical properties of III-V semiconductors differ from those of Si, direct integration of conventional III-V semiconductor photonic devices into Si-based electronic platforms is very difficult and challenging. Therefore, there has been strong demand for efficient Si-based light-emitting devices, especially visible-light sources for optical data transmissions using inexpensive plastic fibers or waveguides. In this work, we demonstrate reddish-yellow visible-light emission in Si-based surface LEDs, operating continuously at room temperature. Figure 1 shows the structure, lattice image, and photographs of our LED device. Our LEDs are based on the optical transitions between the *p-d* hybrid orbitals of manganese (Mn) dopant atoms in Si (Si:Mn). To overcome the low solubility of Mn in Si, we used a low-temperature molecular-beam epitaxy technique to grow high-quality Si:Mn films with Mn concentrations of up to 1.6% (8×10^{20} cm^{-3}). A band engineering technique was used to design appropriate Si-based p-n junctions containing Si:Mn for the LEDs, such that for a reverse bias voltage of −3 to −6 V, an intense electric field (up to ~10^6 Vcm^{-1}) builds up in the depletion layers of the p-n junctions. This electric field accelerates the charge carriers to sufficiently high energy, such that these hot carriers excite the *p-d* hybrid states of Mn by impact excitation; this leads to visible-light emission at room temperature, due to the optical transitions from the excited *p-d* states to the lower *p-d* states. Above a threshold reverse bias voltage of −4 V, our LEDs show strong visible-light emission with two peaks at 1.75 eV and 2.30 eV. Furthermore, we demonstrated digital data transmission using direct amplitude modulation of our LEDs, up to 1 Mbps, which is limited only by the RC time constant of our LEDs. This implies that the present Si-based LEDs can be monolithically integrated into Si electronic devices and circuits, and can be used for visible-light optical data transmission, an especially promising attribute for chip-to-chip and board-to-board optical interconnections. This work is supported by Grant-in-Aids for Scientific Research including the Specially Promoted Research, and the Project for Developing Innovation Systems of MEXT.

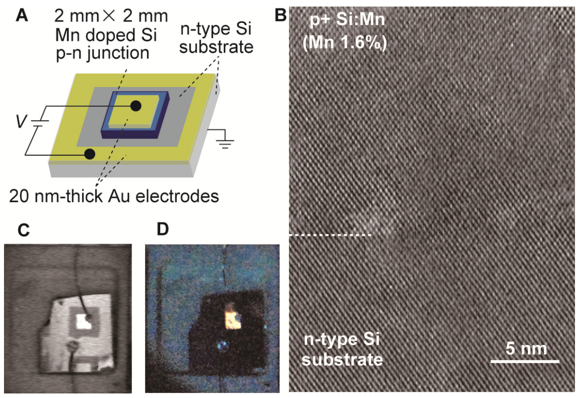

Fig. 1. (A) Schematic device structure of our Si surface LEDs. **(B)** Cross-sectional transmission electron microscope (TEM) lattice image of a LED with a structure of p+ Si:Mn / n-type Si. **(C)** Monochrome and **(D)** color picture of a LED when biased with a bias voltage of −4.7 V and a current density of −7.5 A/cm^2 at 300 K.