Luminescence properties of silicon nanocrystals in Al₂O₃ fabricated at low temperature

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I. INTRODUCTION

NANOSTRUCTURED silicon has been intensely studied for over 15 years as a potential enabling material for silicon photonics [1]. Typically silicon nanocrystals are studied in a silicon oxide host matrix, which provides excellent surface passivation that ensures high radiative quantum efficiency. However other host matrices are of technological and scientific interest, particularly those that are compatible with CMOS back-end processing. Here we present spectroscopic measurements of silicon nanocrystals in alumina (Al₂O₃) fabricated by low-temperature methods [2]. This material exhibits near-infrared and visible photoluminescence (PL) and electroluminescence (EL) as deposited. The luminescence intensity can be increased by low-temperature annealing in a hydrogen-rich atmosphere. Time resolved luminescence measurements show PL decay rates on the order of 1 MHz, suggesting that the luminescence can be attributed to exciton recombination in silicon nanocrystals.

II. EXPERIMENTAL

Silicon nanocrystals are grown by alternating between alumina deposition by atomic layer deposition (20 nm) and silicon deposition by plasma-enhanced chemical vapor deposition (3 nm) on 100 mm silicon substrates at low temperature (T < 300 °C). A similar structure is shown in Fig. 1. Five layers of each material were deposited for a total film thickness of ~100 nm. The wafers are then diced into cm² samples, some of which are annealed in forming gas (10% H₂ in N₂) for 30 minutes at temperatures up to 500 °C.

Photoluminescence is excited using the 488 nm line of an Ar⁺ laser and spectra are measured with a grating spectrometer and CCD camera. Excitation powers are typically of order 1 W/cm². For electroluminescence measurements, metal-insulator-silicon (MIS) capacitor structures are formed by sputtering semi-transparent gold contact structures. A DC current is passed through the active layer by a programmable voltage source at up to 100 V. Time-resolved spectra are recorded using a grating spectrometer, a photomultiplier tube, and a multichannel scaler. An acousto-optic modulator is used to switch the pump laser while driving currents are controlled using an arbitrary function generator and a simple emitter-follower circuit. The system time response is better than 1 μs.

Figure 1. A high resolution transmission electron microscope cross-sectional image showing the multilayer structure of silicon nanocrystals and alumina.

Figure 2. Typical photoluminescence spectra showing the enhancement of luminescence after annealing in a hydrogen-rich forming gas atmosphere.

Photoluminescence spectra show a broad peak centered at approximately 850 nm, which increases up to 400% in intensity after passivation in forming gas, as shown in Fig. 2. Time-resolved measurements show complex decay dynamics characterized by multiple time constants, with a significant component persisting over microsecond timescales (Fig. 3). Typical electroluminescence spectra show a slight red-shift but are otherwise similar to the photoluminescence results (Fig. 4). Time-resolved electroluminescence decay data are shown in Fig. 5.
III. RESULTS AND DISCUSSION

Our measurements contrast with previously published work on silicon nanocrystals fabricated by Si⁺ ion implantation into sapphire substrates [3, 4] in which the characteristic near-infrared photoluminescence band has not been clearly observed. However our data are similar to recent results for co-sputtered silicon-rich Al₂O₃ films [5]. The time-resolved photoluminescence decay data reveal further similarities between the emission characteristics of silicon nanocrystals deposited in alumina and nanocrystals in silicon oxide matrices. This suggests that the surface coordination of the silicon nanocrystals is similar in both systems; the nanocrystals may be passivated by a thin shell of silicon oxide within the alumina matrix.

![Figure 3](image1.png)

**Figure 3.** A typical time-resolved photoluminescence decay curve for the as-deposited material measured at 780 nm. The 488 nm pump laser is switched off abruptly at 0.2 msec.

The mechanism of electroluminescence is highly likely to be impact ionization by hot electrons. We have observed a decrease in the emission intensity over minute timescales that we attribute to accumulating damage in the alumina matrix. The power efficiency of electroluminescence is much less than 1% in our devices.

IV. CONCLUSIONS

Optically active silicon nanocrystals can be incorporated in alumina (Al₂O₃) using low-temperature CMOS-compatible processing. Luminescence is tentatively attributed to exciton recombination in silicon nanocrystals and associated oxygen related surface states.

REFERENCES


