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Investigation of photoluminescence emission in Al-N co-doped 6H-SiC by temperature-dependent measurements

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White light sources based on light-emitting diodes (LEDs) are enjoying an expanding access to the lighting market due to their low energy consumption. The conventional LED-based white light sources have certain limitations such as the use of scarce rare-earth elements, the droop effect and constraints to achieve high color quality. These situations call for alternative solutions such as novel light-emitting materials. Fluorescent silicon carbide (f-SiC) is a promising candidate with exceptional material properties such as excellent thermal conductivity which simplifies heat management at high power operations, high radiation resistance, high breakdown voltage and capability to produce excellent color quality [1-4]. Donor-acceptor pair (DAP) recombination of a nitrogen (N) and aluminum (Al) co-doped silicon carbide can emit blue light at low temperatures. The capability to generate blue emission at room temperature is of paramount importance for the development of f-SiC based white light sources. The physical mechanism by which the emission is suppressed at high temperatures is not well-established yet.

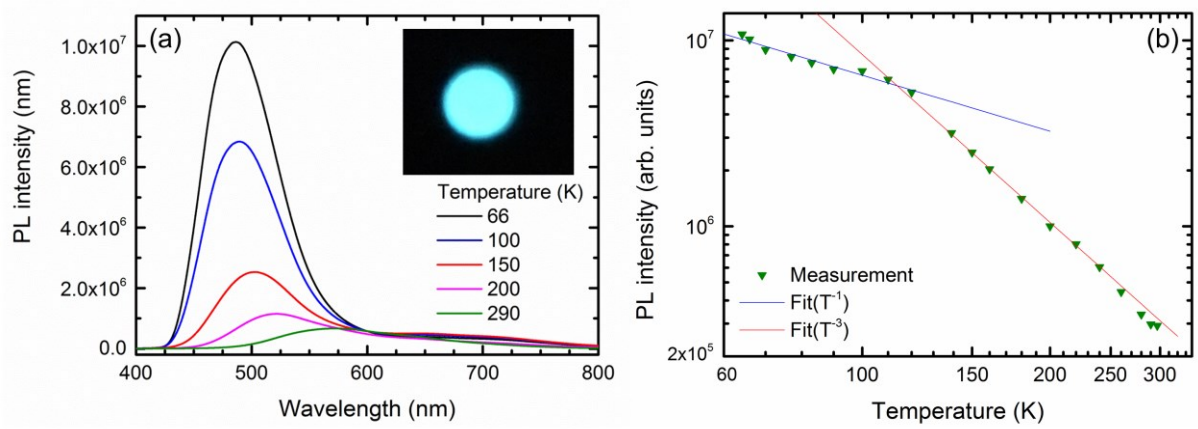
Temperature-dependent photoluminescence (PL) in N-Al co-doped 6H-SiC, which is grown by fast sublimation growth process (FSGP) [5], is measured. A CW laser (center wavelength at 375 nm) is used to excite the sample. The PL spectra of a sample at different temperatures are shown in Fig. 1(a). The epilayer growth is conducted at 1920 ^{o}C where the nitrogen pressure is set to 3 mbar. The dopant concentration is measured by time-of-flight secondary ion mass spectrometry (TOF-SIMS) and the concentrations of N and Al are $1.1\pm0.38\times10^{19}$ and $1.78\pm0.04\times10^{18}$ respectively. The peak wavelength at 66 K is approximately 485 nm and red-shifts with increasing temperature. The color composition of the emission covers the blue and green spectral regions which looks Cyan in the camera image shown in the inset of Fig. 1(a). The combination of the cyan emission from N-Al co-doped f-SiC and a yellow emission from boron-nitrogen co-doped f-SiC will result in a white light source with exceptional color quality.

To look into the physical mechanism of the emission in more detail, the dependence of the peak emission intensity as a function of temperature is characterized as shown in Fig. 1(b). The temperature dependence shows an interesting trend such that at low temperatures the peak intensity is inversely proportional to temperature while it shows an inverse proportionality to the cubic temperature at higher temperatures. We note that the emission intensity does not follow an exponential relationship with the inverse of temperature in our measurement range. This indicates that the suppression of PL intensity at room temperature is not associated with thermal quenching in relation to ionization of free carriers from the dopant states. In such cases the PL intensity is expected to follow the Boltzmann distribution such that, $I_{PL}(T) \propto \exp(-E / K_B T)$ where E is the binding energy of the donor/acceptor state, K_B is Boltzmann constant and T is temperature.

Temperature dependence similar to that of the PL emission from Al-N co-doped SiC has been observed in other semiconductors such as Si and Ge [6]. The observed dependence is the nature of free carrier capture process by attractive trap centres [7]. At high temperatures electron-phonon collisions are quasielastic and carriers interacting with phonons lose and acquire energy in small portions which can be explained by the classical energy diffusion theory. As a result of gradual loss of energy, free carriers will be captured when their energy drops below the level of the binding energy. In this case the capture cross-section is inversely proportional to cubic temperature, *i.e.* $\sigma \propto T^{-3}$. At low temperatures, emission of a single phonon with subsequent capture into a highly excited dopant state results in carrier binding to the trap state. Here the temperature dependence of the capture cross-section weakens to an inverse proportionality, *i.e.* $\sigma \propto T^{-1}$. Inverse temperature dependence is expected if the capture is dominated by the emission of high energy optical or intervalley phonon and the thermal energy is much less than the energy of these phonons. Since the PL intensity is proportional to capture cross-section, the PL intensity tends to follow the same temperature dependence.

In summary temperature-dependent PL measurements reveal that the low capture rate of free carriers by a DAP caused low emission intensity at room temperature. As the capture cross-section of DAP decreases at high temperatures, competing non-radiative recombination channels dominate the free carrier recombination. The achievement of a strong emission from Al-N co-doped 6H-SiC samples at room temperature through suppression of non-radiative recombination pathways by defect management and optimization during growth will facilitate the development of white light sources from fluorescent silicon carbide.

Fig. 1(a) PL emission spectrum from N-Al co-doped 6H SiC at various temperatures. The inset shows the camera image of PL emission at 66K. (b) Measured peak PL intensity as a function of temperature and the fits. Note that both the y-axis and the x-axis are in a logarithmic scale.



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