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Carrier Dynamics in Nanoscale Light-Emitting Diodes

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Abstract-Nanoscale light sources operating efficiently at low powers are required for future optical interconnects. Here, we present, both theoretically and experimentally, the carrier dynamics in metal-dielectric cavity nanopillar light-emitting diodes. The nanoLEDs operate at telecommunications wavelengths, featuring tens of nanoWatt waveguide-coupled powers and GHz-range modulation bandwidths. Furthermore, an extremely low surface recombination velocity of 260 cm/s in passivated InGaAs nanopillars is reported, a result of crucial importance for the development of efficient nanoscale optoelectronic devices for nanophotonic integrated circuits.

Electronic data connections are increasingly becoming a bottleneck in the exponential growth of data traffic worldwide. Future optical interconnects are the obvious successors but will require ultrasmall light sources with sub-micrometer sizes to achieve low energy consumption (<10 fJ/bit), and ultrafast speeds [1]. Nanoscale light sources have been developed recently using either metal, metallo-dielectric or photonic crystal nanocavities [2]. Despite much progress, nanolasers and nano-light-emitting diodes (nanoLEDs) operating efficiently at low powers and suitable for photonic integration are lacking. Among numerous challenges, in both light-emitting diodes and lasers, radiative and nonradiative recombination rates play a key role in the efficiency. Radiative recombination (both spontaneous and stimulated) is affected by the small mode volume in nanoLEDs and nanolasers, potentially leading to strong Purcell enhancements and higher speed [3,4]. On the other hand, nonradiative recombination rates, specifically surface recombination rates, are also very high due to the high surface-to-volume ratios [5], typically leading to low radiative efficiencies.

Here, the authors present recent work on waveguide-coupled metal-dielectric cavity nanopillar LEDs on silicon working at telecommunications wavelengths [5], and featuring more than 20 nW waveguide-coupled powers and GHz-range modulation bandwidths at room-temperature (RT). The efficiency of the reported nanoLEDs currently lies between 0.01 and 1 percent, at RT and at 10 K, respectively, mostly limited by nonradiative recombination effects. We show that a passivation method using sulfur treatment, followed by silicon oxide capping deposited by plasma-enhanced chemical vapor deposition, strongly suppresses the surface recombination at the InGaAs surfaces of nanopillars from a few hundred picoseconds to more than 20 nanoseconds [6]. The estimated surface recombination velocity, decreases from about 2×10^4 cm/s in the untreated nanopillars down to around 260 cm/s. To our knowledge, this is a record low value in undoped InGaAs semiconductors. Most importantly, our passivation studies reveal that the SiO_x capping layer not only protects the pillars' sidewalls against oxidation, as reported in [7], but actively takes part in the passivation process. This will ensure substantial improvements in the efficiency of future nanoLEDs and reduce the threshold current in nanolasers, which are of crucial importance for their application in optical interconnects.

Finally, the performance of the experimental nanoLEDs is analyzed using a rate equations model which properly takes into account the nanocavity effects in the spontaneous emission rate and the spatial and spectral overlap between carriers and photons. The ultimate limits of scaling down these nanoscale light sources leading to Purcell enhancement of the emission and higher speeds are also theoretically analyzed.

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