Fast and Slow Light-Emitting Silicon-Germanium Nanostructures

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Optical interconnects are now being considered for on-chip interconnects as an alternative to metal wires [1]. Two major avenues toward optical interconnects on a chip include a hybrid approach and the all-group-IV approach [1, 2]. Efforts in the past on obtaining light emission from group-IV semiconductors have been mainly focused on Si/Ge nanostructures (NSs) [2]. However, no approach has so far overcome a long carrier radiative lifetime and the significant thermal quenching of the luminescence quantum efficiency [2]. By the 1990s, a different form of SiGe NS, namely the three-dimensional (3D) self-assembled system, had been demonstrated [3]. Compared to previous Si/SiGe NSs, the photoluminescence (PL) and electroluminescence (EL) quantum efficiency in 3D Si/SiGe NSs is higher (up to ~1%), especially for T > 50 K. The proposed further development of 3D Si/SiGe based light emitters was discouraged by several studies indicating a type II energy band alignment at Si/SiGe heterointerfaces, where the spatial separation of electrons (located in Si) and holes (localized in SiGe) was thought to make carrier radiative recombination very inefficient. Here, we show that it is possible to obtain conditions favorable for efficient carrier radiative recombination.

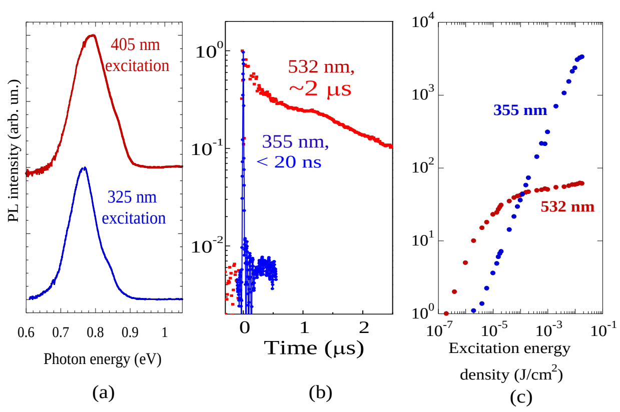

Figure 1. (a) Normalized PL spectra for different excitation wavelengths. (b) PL decays measured at 0.78 eV under ~6 ns duration excitation for different excitation wavelengths. (c) PL intensity as a function of excitation energy density for different excitation wavelengths. The sample temperature was 15 K.

PL measurements were performed on a specially engineered nine-period multilayered Si/SiGe NS with a nominal Ge concentration approaching ~35% [4, 5]. Using photo-excitation of 405 nm wavelength (~0.1 µm penetration depth), we observe a PL spectrum with a full width at half maximum (FWHM) of ~130 meV [see Fig.1(a)]. On using photo-excitation at 325 nm (~10 nm penetration depth), we find the PL spectrum slightly shifted to lower photon energy and with a significantly reduced FWHM (~100 meV). This result indicates that the variation in SiGe NS composition and Si/SiGe interface abruptness (see Ref. [5]) are reflected in the PL spectra: in the top SiGe layer, a higher Ge composition results in the PL peak being shifted toward lower photon energy, and the more abrupt Si/SiGe interface is responsible for the reduced FWHM of the PL peak.

Figures 1(b) and (c) compare PL lifetimes and PL intensity as a function of excitation energy density measured under pulsed laser excitation with a pulse duration of ~6 ns. We find that PL excited at 532 nm and recorded at 0.78 eV (which originates from the lowermost Si/SiGe NS layers) has a lifetime approximately 100 times longer compared to the same PL excited using 355 nm (PL from the topmost Si/SiGe NS layers). The shortest observed PL lifetime for 3D SiGe NSs is less than 20 ns, and it is independent of excitation energy density until a very high level of excitation. We carefully investigated the PL decay under 355 nm excitation with energy densities varied from 10^{-5} to 5×10^{-2} J/cm^2. No changes in the PL lifetime are found until the Auger limit has been reached, with a carrier concentration approaching ~10^{19} cm^{-3}. On the contrary, the PL decay under 532 nm excitation accelerates while the PL intensity saturates as a function of excitation energy density (not shown). Also, we find a dramatic difference in the PL intensity as a function of excitation energy density for excitation at different wavelengths: the PL intensity under 532 nm excitation quickly saturates while under 355 nm excitation the PL intensity is linear versus excitation intensity for many orders of magnitude [Fig. 1(c)]. At the same time, at low excitation the PL intensity under 532 nm excitation is ~10 times higher compared to the PL excited by 355 nm. Most likely, this difference is due to a higher contribution of non-radiative surface recombination for the shorter wavelength excitation.

The results presented here demonstrate that in Si/SiGe 3D NSs the PL peaked near 0.78 eV strongly depends on the Si/SiGe heterointerface abruptness. Our measurements show that in MBE-grown low defect density 3D Si/SiGe NSs a transition from pure Si to $Si_{1-x}Ge_x$ with $x \approx 0.3$–0.4 may require an interface width of more than 5 nm. These diffused type-II Si/SiGe heterointerfaces are responsible for significant (d > 5 nm) electron-hole spatial separation and slow PL, which cannot compete with Auger recombination even at low excitation intensities. However, by engineering more abrupt Si/SiGe heterointerfaces with d ≈ 3 nm, we find a PL lifetime of < 20 ns, which is only a little longer than that found in direct band-gap III-V semiconductors. This extremely fast PL has a quite high quantum efficiency, which, in contrast to previous reports, remains constant over many orders of magnitude of excitation intensity.

In other Si/SiGe NS/quantum-well samples with a Ge concentration approaching ~40%, we find two PL bands peaked at 0.8 eV and 0.95 eV at low temperatures. The PL peaked at 0.8 eV rises and decays slowly, and it quickly saturates as the excitation intensity increases. In contrast, the PL peaked at 0.95 eV shows a much shorter lifetime and exhibits a linear dependence versus excitation intensity. The slow/delayed PL at 0.8 eV is attributed to carrier recombination at the SiGe NS/Si transition layer while the faster and more efficient PL at 0.95 eV is associated with SiGe quantum wells.

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