Electroluminescence of Ge/Si self-assembled quantum dots grown by chemical vapor deposition

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We have fabricated light-emitting diodes on Si operating in the near-infrared. The active region of the $p-i-n$ diodes consists of Ge/Si self-assembled quantum dots. The Ge islands were grown in an industrial 200 mm single-wafer chemical vapor deposition reactor. The photoluminescence and the electroluminescence of the islands are resonant in the spectral range around 1.4–1.5 μm wavelength. The electroluminescence is observed up to room temperature. © *2000 American Institute of Physics.* [S0003-6951(00)00437-X]

The development of optical networks based on wavelength division multiplexing is stimulating the research for low-cost optical components. These optical components, which include optical sources, modulators, and photodetectors are expected to operate in the near-infrared spectral range around the 1.5 μm wavelength. One possibility for significant cost reduction is to integrate these optical components on Si chips. One obvious advantage of the monolithic integration of devices on Si is their compatibility with Si-based electronics and technology. Important efforts are now directed towards this direction. High-speed near-infrared Ge photodetectors integrated on Si substrates were recently reported.[1]

Several routes have been investigated in the recent years to integrate an optical emitter operating at the 1.5 μm wavelength on Si. The incorporation of rare-earth atoms into silicon was extensively studied. Erbium-based emitters take advantage of the intra-4f shell transitions resonant at 1.54 μm. Room temperature electroluminescence of erbium-doped silicon light emitting diodes were reported by several groups.[2,3] The growth of ultrathin Si_mGe_n superlattices was also investigated.[4] The study of short-period superlattices was motivated by the possibility to achieve a pseudodirect band-gap semiconductor by zone folding. Room-temperature electroluminescence resonant up to 1.35 μm was also observed with Si/Ge/$Si_{1-x}Ge_x$ quantum well diodes.[5] The active region was a two-well pure Ge quantum structure (2 and 4 monolayers thick) separated by a silicon quantum well. Another route to realize Si-based optoelectronic devices operating at 1.5 μm is based on the integration of self-assembled quantum dots. The growth of Ge/Si self-assembled quantum dots can be achieved using the Stranski–Krastanow growth mode allowed by the lattice mismatch between Ge and Si.[6] Only few articles have been devoted to the electroluminescence of Ge/Si islands while the photoluminescence of these islands has been extensively studied.[7–9] The electroluminescence of SiGe self-assembled dots fabricated by low-pressure chemical vapor deposition was reported by Apetz *et al.*[10] In that case, the nominal composition of the islands was not pure Ge and the electroluminescence signal observed around 1.35 μm was very similar to that of $Si_{0.8}Ge_{0.2}$ alloys.

In this work, we report on light emitting diodes based on Ge/Si self-assembled quantum dots. The devices exhibit a broad emission peaked around 1.45 μm. The electroluminescence is observed up to room temperature.

The self-assembled quantum dots were grown in an industrial lamp-heated single wafer chemical vapor deposition (CVD) reactor.[11,12] The wafers were 200 mm diameter (001) oriented Si substrates. Silane and germane diluted in hydrogen carrier gas were used as gas precursors. The process temperature deposition was in the 550–700 °C range, at a total pressure lower than 100 Torr. The typical deposition time for a single layer of Ge dots and for the Si barrier was smaller than 1 min. These process times are compatible with both reproducibility and throughput basic requirements for a future industrialization. The CVD deposition sequence to achieve the active electroluminescent structure is as follows: a 550-nm-thick p^+ Si layer *in situ* doped with boron ($10^{19}\,cm^{-3}$) using B_2H_6 diluted in H_2, a 200-nm-thick Si spacer layer, five layers of Ge islands separated by 35-nm-thick Si barrier layers, a 200-nm-thick Si spacer layer, and a 80-nm-thick n^+ contact layer *in situ* doped with AsH_3 diluted in H_2 ($10^{19}\,cm^{-3}$). All the structure was elaborated with a low thermal budget. The growth conditions for the Ge islands were similar to that reported in Ref. 11. The dot density is around $1.7\times10^{10}\,cm^{-2}$. The quantum dots of a single

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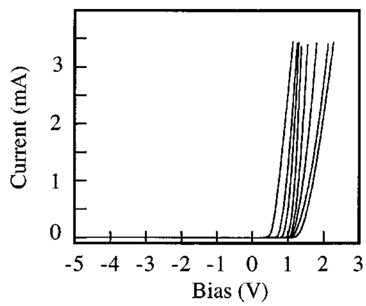

FIG. 1. Current–voltage characteristics of the *p–i–n* diodes as a function of temperature. From left to right: 290, 200, 140, 80, 45, 30, 20, and 11 K.

Ge layer grown in the same conditions have a typical base size of 50 nm and an height of 4 nm.

The diodes were processed into $300\times300\,\mu$m devices by reactive ion etching. A $100\times100\,\mu$m optical window was open on top of the structure for light coupling. The ohmic contacts with the p^+ and the n^+ layers were obtained by depositing Ti/Au contacts. The walls of the mesas were not passivated. The silicon chip was glued to a ceramic pedestal. The top and back contacts were bonded with gold wires using standard thermocompression bonding. The photoluminescence and electroluminescence spectra were measured with a liquid–nitrogen cooled Ge photodiode. The photoluminescence was excited with an Ar^+ laser. The electroluminescence was excited with square electrical pulses at low frequency with a 1:1 duty cycle.

Figure 1 shows the current–voltage characteristics of the diodes as a function of the temperature. A very weak leakage current is measured under negative bias. At room temperature, the reverse current is lower than 4 μA ($\sim 4\times10^{-3}$ A cm^{-2}) for a negative bias of -5 V. At room temperature, the ideality factor of the diode is $\sim$2. The ideality factor first starts to increase as the temperature decreases. The ideality factor then decreases for temperatures below 50 K. This variation indicates a change in the transport and in the recombination of the carriers across the *p–i–n* junction. As shown below, a significant change in the electroluminescence signal is also observed as the temperature decreases below 50 K.

Figure 2 shows the low-temperature photoluminescence spectra of the unprocessed sample for two excitation densities (1 W cm^{-2} and 1 kW cm^{-2}). The photoluminescence spectra are dominated by two groups of lines. The recombination lines around 1100 and 1060 meV are associated with the photoluminescence in the Si spacer layer and in the Si-doped layers, respectively.[13] The broad recombination band at low energy, resonant at 800 meV ($\sim$1.5 μm), is attributed to the Ge self-assembled quantum dots. The full width at half maximum is $\sim$80 meV. As the temperature is increased, the photoluminescence of the doped silicon vanishes and the radiative recombination of the quantum dots dominate. Two maxima separated by $\sim$50 meV can be observed in the quantum dot recombination spectra. The intensity ratio between these two maxima is modified as the excitation density is increased. Photoluminescence spectra similar to that observed at high excitation density have been measured in the weak excitation regime in separate experiments for quantum dot samples with ten multiple layers. We attribute the occurrence of these two resonances to a variation of the quantum dot size and composition from layer to layer rather than to the recombination associated with the excited levels of the dots.[14] The photoluminescence related to the wetting layers is not observed because of the large density of the islands. We emphasize that the resonance energy of the photoluminescence is correlated to the composition and to the size of the quantum dots. Selected-area transmission electron diffraction measurements performed on a single quantum dot layer have previously shown that the average Ge content of the dots was around 40%.[15] The resonance of the photoluminescence around 1.5 μm wavelength is therefore mainly associated with the alloying between Ge and Si within the quantum dots.

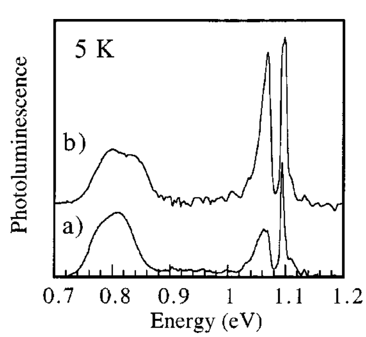

FIG. 2. Low-temperature (5 K) photoluminescence of the unprocessed sample. (a) corresponds to an excitation density of 1 W cm^{-2} delivered by an Ar^+ laser. (b) corresponds to an excitation intensity of 1 kW cm^{-2}. The curves have been offset for clarity.

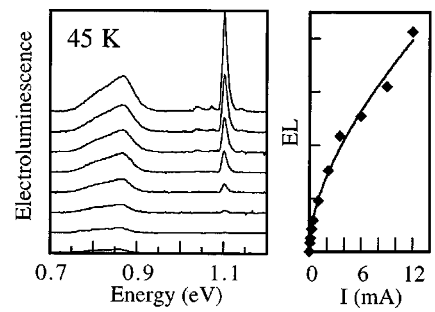

FIG. 3. Electroluminescence at 45 K as a function of the current density (from bottom to top: 0.27, 0.44, 1.1, 2.44, 3.85, 6.6, 9.9, and 13.2 A cm^{-2}). The curves have been offset for clarity. The right-hand side of the figure shows the integrated electroluminescence signal of the Ge/Si islands as a function of the current density. The full curve is a guide to the eyes.

Figure 3 shows the electroluminescence spectra measured at 45 K as a function of the current density. The electroluminescence is characterized by the radiative recombination in the silicon undoped layers (1100 meV) and a broad emission resonant around 850 meV (1.45 μm). By analogy with the photoluminescence spectroscopy, the broad emission at low energy is attributed to the radiative recombination in the quantum dot layers. The broadening of the emission is around 100 meV. Electroluminescence and photoluminescence exhibit very close resonance energies. The slight energy blue-shift of the electroluminescence as compared to the photoluminescence is attributed to the inhomogeneity of the quantum dots in the vertical stacking. The dependence of the integrated electroluminescence signal of the Ge/Si islands on the current density is also shown in Fig. 3. The integrated electroluminescence exhibits a linear de-

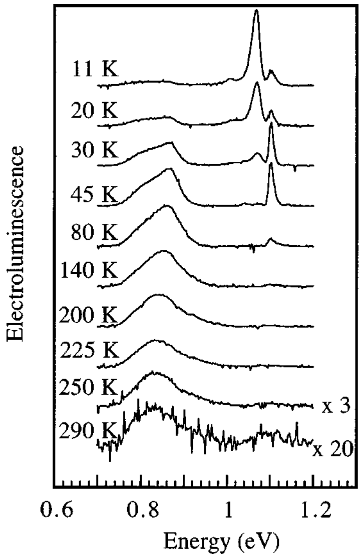

FIG. 4. Temperature dependence of the electroluminescence. The sample temperature is indicated on the left of the curve. The current density is kept constant ($3.85\ \mathrm{A\,cm^{-2}}$). The curves have been offset for clarity. The curves recorded at 250 and 290 K have been multiplied by a factor of 3 and 20, respectively.

pendence for weak current densities while a sublinear dependence is observed for the integrated signal at higher current densities.[10] This sublinear behavior was also observed for the photoluminescence of the quantum dots of the unprocessed sample. The emitted power, which is collected from the $100\times 100\ \mu$m optical window, is of the order of 20 nW.

The temperature dependence of the electroluminescence is shown in Fig. 4. The measurements were performed with a constant current density of 3.5 mA ($3.9\ \mathrm{A\,cm^{-2}}$). At low temperature, the electroluminescence amplitude of the quantum dots is weak. The radiative recombination is dominated by the recombination in the silicon doped layers. As the temperature increases, the electroluminescence associated with the silicon doped layers is progressively quenched. Meanwhile, the recombination efficiency in the quantum dot layers increases. This feature should be compared with the modifications also observed on the current–voltage characteristics. The electroluminescence is then roughly constant up to 225 K and starts to decrease above this temperature. We emphasize that the electroluminescence can be observed up to room temperature. The amplitude of the integrated electroluminescence is only reduced by a factor of ~30 as the sample temperature increases from 80 K to room temperature. The electroluminescence shifts to lower energy as the temperature is increased and is resonant at ~1.5 μm at room temperature. An activation energy of 230 meV can be estimated from the quenching of the electroluminescence signal with temperature. This quenching is associated with the effective barrier height for the holes in the valence band.[16] The barrier height that limits the thermionic emission of the holes roughly corresponds to the energy difference between the photoluminescence energies of the Si substrate and of the Ge quantum dots. We emphasize that only five Ge/Si quantum dot layers were present in the investigated structure.

In summary, we have reported on $p-i-n$ light-emitting diodes on Si whose active region consists of Ge/Si self-assembled quantum dots grown by chemical vapor deposition. Both electroluminescence and photoluminescence occur near 1.5 μm. The electroluminescence intensity is maximum up to 225 K and starts to decrease at higher temperature. The electroluminescence is observed up to room temperature. This work demonstrates the interest of Ge/Si self-assembled quantum dots for low-cost optical emitters integrated on Si and operating at the telecommunication wavelengths.

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