Cavity-enhanced direct band electroluminescence near 1550 nm from germanium microdisk resonator diode on silicon

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We electrically and optically characterize a germanium resonator diode on silicon fabricated by integrating a germanium light emitting diode with a microdisk cavity. Diode current-voltage characteristics show a low ideality factor and a high on/off ratio. The optical transmission of the resonator features whispering gallery modes with quality factors of a few hundred. Direct band gap electroluminescence under continuous current injection shows a clear enhancement of emission by the cavity. At this stage, the pumping level is not high enough to cause linewidth narrowing and invert the material. A higher n-type activated doping of germanium is necessary to achieve lasing. © 2011 American Institute of Physics. [doi:10.1063/1.3592837]

A silicon (Si) compatible electrically pumped laser for applications in optical telecommunications and optical interconnect systems[1] has been an interesting topic for several years now but has yet to be practically demonstrated. Germanium (Ge) has recently attracted much attention as a possible complementary metal-oxide semiconductor (CMOS)-compatible light emitter that can be integrated well on-chip. However, bulk Ge has an indirect band gap and, therefore, is a poor optical emitter. Due to the small energy difference between its indirect L valley and direct Γ valley, several approaches have been proposed to improve Ge luminescence properties, including tensile strain,[2] tin alloying,[3] and electron band filling.[4] We pursue the last approach since the emission wavelength can be maintained near 1550 nm. Previously, there have been several reports showing improvement of direct gap photoluminescence (PL) from band filling.[5,6] Room temperature direct band electroluminescence (EL) from Ge light emitting diodes (LEDs) on Si was also demonstrated by several groups.[7–9] An optically pumped Ge on Si laser with a large Fabry–Perot cavity structure was demonstrated by Liu et al.,[10] showing the high potential of this band filling approach. We have recently also reported optically pumped Ge microdisk resonators and observed clear cavity-enhanced direct gap PL.[11] All of the above research efforts are bringing us closer to the goal of achieving electrically-pumped Ge lasers on-chip, but in order to fulfill this objective, a Ge LED and a resonant cavity need to be integrated together. A microdisk resonator diode from Ge quantum dots on Si-on-insulator was recently demonstrated.[12] However, a resonator diode coupling direct gap Ge emission on Si has not yet been shown. In this work, we design and demonstrate Ge microdisk resonator diodes on Si by combining a microdisk resonator with an epitaxial Ge LED. This technique is a useful template to study and pursue Ge gain or lasing in the future.

The cross-section schematic of the Ge resonator diode is shown in Fig. 1(a). A highly doped p-type (100) Si substrate was used with a resistivity of 0.005 Ω-cm, corresponding to a doping concentration over 1×10^{19} cm^{-3}. A 0.9 μm thick undoped Ge layer was then deposited on this p$^+$ Si substrate by an Applied Materials reduced pressure chemical vapor deposition system. The growth process includes two deposition steps at 400 and 600 °C with the partial pressure of GeH$_4$ at 8 Pa. Hydrogen annealing at 825 °C was done after each deposition step to improve crystal quality. A 200 nm *in situ* doped n$^+$ (1×10^{19} cm^{-3}) Ge layer[13] was subsequently deposited at 600 °C to form the diode junction. It should be noted that we use undoped Ge instead of n-type Ge as the active layer of this LED for obtaining clearer and higher quality resonances, as discussed in our previous work.[11] Photolithography and a reactive ion etching process were applied to form 6 μm diameter Ge disks. The disks were then passivated with a 30 nm thick low temperature oxide (LTO) layer at 300 °C. After opening contact windows, the top and bottom aluminum (Al) contacts were deposited by e-beam evaporation.

For such a small disk diameter, directly probing the top contact is difficult. A connecting Al wire was thus designed
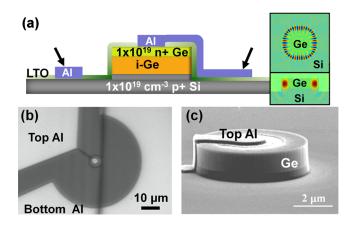

FIG. 1. (Color online) Design of the Ge microdisk resonator diode. (a) Cross-section schematic of the device structure. The profile of the H_z component of the simulated WGM is shown to the right in both top and cross section slices. (b) Plan-view optical image of a fabricated 6 μm diameter resonator diode probed by fiber taper. (c) SEM image of a fabricated resonator diode.

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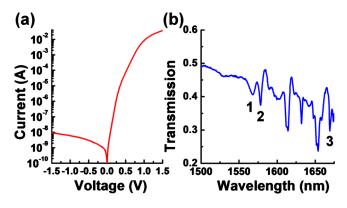
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FIG. 2. (Color online) Electrical and optical properties of the resonator diode. (a) I-V characteristic of the device. (b) Optical transmission spectrum of the device with three resonance modes labeled.
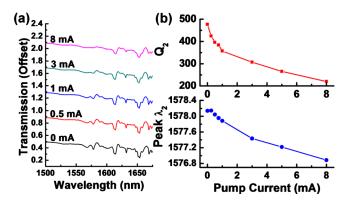

FIG. 3. (Color online) The behavior of cavity modes under increasing pump current. (a) Optical transmission spectra for the resonator diode under continuous pump current. The spectra are offset by 0.4 units for clarity. (b) Cavity mode wavelength and Q factor for peak no. 2 vs continuous pump current.

to bridge the top metal and the side probing pad. To ensure that the injected carriers can spread out to the side of the disk for cavity coupling, the Ge microdisk was not undercut. The drawback is a higher optical loss since the bottom side of the disk is not isolated. However, finite-difference time-domain (FDTD) simulation shows that it is still possible to obtain high quality (Q) factors in certain modes for this structure. The inset of Fig. 1(a) shows a particular transverse electric whispering gallery mode (WGM) at 1630 nm with a Q factor near 1×10^5 (excluding absorption losses). A plan-view optical microscope image and a scanning electron microscope (SEM) image are shown in Figs. 1(b) and 1(c), respectively. The width of the connecting Al wire is minimized to 1 μm to reduce metal loss.

The diode current-voltage (I-V) was initially characterized and shown in Fig. 2(a). The diode exhibits standard rectifying behavior with an ideality factor of 1.25. A high on/off ratio over 1×10^6 is found, indicating good epitaxial Ge quality and a low series resistance. This low series resistance of 16 Ω comes from the high doping concentrations of the p^+ Si substrate and the n^+ Ge layer, as well as from small device dimensions. This allows the diode to be operated at a high current density of 3×10^4 A/cm^2 (8.7 mA) at 1 V before it reaches the series resistance dominated region. The optical properties of the resonator diode are studied in transmission using a side-coupled fiber taper of approximately 1 μm in diameter,[14] as shown in Fig. 2(b). WGMs were observed at wavelengths above 1550 nm, showing that the modified cavity structure has optical properties similar to uncontacted disks.[11] Since the direct band edge is near 1610 nm for epi-Ge on Si with a 0.2% tensile strain,[15] the Q factors of cavity modes below 1610 nm gradually decrease due to increasing direct band absorption.[11] Two cavity modes near 1550 nm can be identified and labeled as peak no. 1 and 2. The Q factors of these two modes are 205 and 477, respectively. The lower Q factors compared to our optically pumped Ge microdisks indicate that there is additional cavity loss. This extra cavity loss originates from the combination of several factors. First, the design without undercut enables photons to preferentially leak to the bottom Si substrate, thereby reducing optical confinement. Second, free carriers in the n^+ germanium layer and p^+ Si substrate cause free carrier absorption (FCA) loss. The effect of doping on FCA in Ge microdisks has already been discussed.[11] Finally, the Al wire on the disk edge and top surface can cause significant metal loss. This excess cavity loss (beyond that due to

material absorption) can be extracted from the modes located in the indirect band region. The Q factor of the cavity mode located at 1669 nm (peak no. 3) is 932, corresponding to 160 cm^{-1} loss. The reported indirect band absorption[16] loss at this wavelength is 30 cm^{-1}, giving an excess cavity loss of 130 cm^{-1}. Since the gain of Ge can reach values above 1000 cm^{-1} under proper band filling condition,[4] our device loss is still small enough to be overcome.

The cavity modes were studied under continuous pump current with a Keithley 2635 source meter. Figure 3(a) shows the behavior of the cavity transmission under various pumping levels. As the pump current increases, the cavity resonances become broader and shallower, indicating a drop in the Q factors. This is similar to the behavior we observed from optically pumped Ge resonators.[11] The possible causes for Q reduction in Ge microdisks are heating and FCA.[11] In order to clarify this, the Q factor and wavelength of peak no. 2 were characterized for increasing pump currents [Fig. 3(b)]. As we increase the pump current from 0 to 8 mA (2.8×10^4 A/cm^2), the Q factor decreases from 477 to 220 and the peak wavelength undergoes a 1.26 nm blueshift. The cause of the Q reduction is then dominated by FCA instead of heating which would have resulted in a redshift in both the direct band edge and cavity modes. Therefore, this device driven at a current density over 10^4 A/cm^2 generates minimal heat and is a promising design for lasing structures. The FCA-driven peak broadening effect comes from the carriers in the Ge indirect L valley and cannot be avoided with the band filling approach.[4] Linewidth narrowing was not observed at this stage, indicating that a higher band filling level is required for the resonator to overcome the FCA and reach material gain.

EL from the Ge resonator diode was collected by connecting the fiber taper output to a spectrometer with a cooled InGaAs detector array. Figure 4(a) shows the output spectrum under a pump current of 0.5 mA. The spectrum consists of both background and cavity mode EL from the direct band gap. Two peaks can be identified which exactly correspond to the labeled cavity modes observed from transmission (1 and 2). Therefore, we obtained cavity-enhanced direct gap EL near 1550 nm from a Ge resonator diode. As we increase the pump current to 3 mA, shown in Fig. 4(b), the peaks broadened, in agreement with the transmission measurement. As discussed above, the injection levels here are too low for
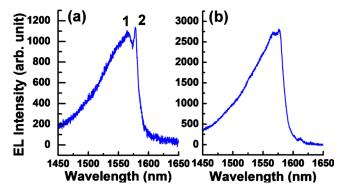
FIG. 4. (Color online) EL spectra from the Ge resonator diode under different pump levels. (a) EL spectrum of the device under continuous 0.5 mA pump current. Peaks labeled 1 and 2 are the same peaks obtained from transmission (b) PL spectrum of the device under 3 mA pump current.

direct band inversion and therefore FCA broadens the mode linewidth.

In summary, we demonstrated the Ge resonator diode on Si by integrating a microdisk resonator with a Ge LED. The I-V characteristics and optical transmission data show good electrical and optical behavior. Cavity-enhanced EL was observed for WGMs near the band edge. The lower Q factors of the modes in this study compared to those in our optically pumped Ge microdisk are due to extra loss from the doping layers and metal contacts. Linewidth broadening was observed under high pumping due to FCA and not heating. A higher activation of the n-type layer is required to invert the device and overcome FCA. With current progress of co-implantation and laser annealing, n-type doping levels in excess of 10^{20} cm^{-3} have been demonstrated in Ge.[17,18] By careful integration of these techniques with a resonator diode, we believe an electrically-pumped Ge laser can be realized.

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