Light Emission in Ge Quantum Wells

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Abstract: We present the Ge/SiGe quantum well structure as a strong candidate for CMOS compatible light source. Photoluminescence and electroluminescence show enhanced optical properties over bulk Ge. Further optical enhancement is observed in disk resonators.

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1. Introduction

The field of Si photonics presents a number of potential benefits, including inexpensive optical devices, optoelectronic integration and optical interconnects. However, obtaining a high quality light source on a Si platform has proven difficult since Si and other common semiconductor materials compatible with CMOS processing have indirect bandgaps. Many advances have been made in using Ge as a light emitting material, with reports of an optically pumped Ge laser[1], and electroluminescence (EL) from Ge bulk, quantum well (QW), and quantum dot (QD) structures [2-4]. In this paper, we present our novel studies on photoluminescence (PL) and EL of a thin Ge/SiGe quantum well structure (with only 3 Ge/SiGe QWs and 500nm SiGe buffer layer on Si wafer) with enhanced optical properties over bulk Ge. We also present a strong cavity mode PL from a Ge QW disk structure, indicating the QW structure’s great potential for future on-chip interconnects.

2. Theory

Although Ge is an indirect bandgap material, Ge has a direct valley only 0.14eV above its indirect valley. As prior work has shown, Ge devices can emit light if sufficient electrons are present such that the indirect valley is filled up to E$_c$(direct) and carriers start populating the direct gap valley. QWs have been employed in conventional III-V light emitting devices to increase efficiency and decrease threshold voltages due to their confinement of carriers. Similarly, a SiGe/Ge QW structure increases carrier density inside the Ge quantum well region, such that a stronger luminescent effect or larger optical gain can be achieved.

3. Material growth and device fabrication

The devices were epitaxially grown on a Si (001) substrate using RPCVD. To decrease the defect density and surface roughness, the quantum wells are grown on p-type Si$_{0.12}$Ge$_{0.88}$ buffer layers that undergo high temperature hydrogen anneal. Three quantum wells were grown, and the structure was capped with a layer of n-type Si$_{0.12}$Ge$_{0.88}$. Disks and mesa structures were patterned and etched using standard fabrication processes, and SEMs of the devices are shown in Fig. 1 and Fig. 2, respectively.

4. Photoluminescence

Fig 1. Ge/SiGe quantum well microdisk
Fig 2. 200 µm x 200 µm Ge/SiGe quantum well PIN mesa
Fig 3. Photoluminescence of Ge quantum well sample
PL measurements were done on a 2 µm-thick bulk-like Ge layer on a Si (001) substrate, a 200 nm-thick thin Ge layer sample grown on a Si substrate and the sample with three QWs. The PL signal energy of the QW sample, displayed in Fig. 3, shows that the signal is from the Ge QW material and not from the SiGe buffer. Furthermore, the PL signal of the QW sample (~40 nm of Ge material) is significantly stronger than that of the thin film Ge sample (200 nm of Ge material). The blue-shift in energy compared to the bulk-like sample is attributed to the carrier confinement in the quantum wells and to compressive strain. The cut-off at 0.75 eV and 0.9 eV are due to the decrease of photodetector responsivity and the long pass filter in the system, respectively. PL measurements were also conducted on the disk structure with a vertical-pump—980 nm diode laser—vertical-collection setup. The results in Fig. 4 show an enhancement of the PL signal over that from the bulk sample mainly due to the strong scattering from the disk sidewall of the disk sample. The fringes in the PL spectrum show a strong excitation of the whispering gallery cavity modes and interference inside the disk cavity. Each of the fringes contains two small peaks, most probably from the TE and TM modes. The quality factor of the device is ~150.

Fig 4. Photoluminescence of Ge quantum well disk structure

Fig 5. Electroluminescence of Ge quantum well PIN diode

Fig 6. Electroluminescence intensity as a function of current density

5. Electroluminescence

EL measurements were conducted on 200 µm × 200 µm PIN Ge QW mesas, and the results are shown in Fig. 5. The red shift of the peak wavelength is caused by band gap shrinkage at higher temperatures at higher currents. The EL intensity, shown in Fig. 6, is superlinear with current density as more electrons are thermally distributed to the direct bandgap valley at higher temperatures.

6. Conclusion

In this paper, we have presented stronger PL intensity from Ge QW structures than that of corresponding bulk Ge structures, which shows a higher carrier density in Ge quantum wells. Strong fringes from a resonant disk structure imply a significant coherent interference effect. We have also presented the light emitting properties of a Ge quantum wells structure. All of the results show that the SiGe/Ge QW structure has great potential to be a good laser source for Si photonics.

References