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SiGe Quantum Well Metal-Insulator-Semiconductor Light-Emitting Diodes

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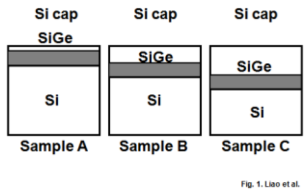
1. Introduction

The Si-based light emitters attract a lot of attention recently for the full integration of electrical and optical devices, due to the compatibility with Si electronics [1-4]. Our group developed and demonstrated the first Si [5], SiGe quantum dot (QD) [6], bulk Ge [7], and SiGe quantum well (QW) [8] metal-insulator-semiconductor (MIS) light emitting diodes (LED) to emit ~1.1 μm, ~1.5 μm, ~1.8 μm, and ~2.0 μm light emission in the decade for the different applications, respectively. MIS LED has many advantages. It can be fully comparable with the modern VLSI process. It is note that the building device in VLSI process is the MIS structure, not a p-i-n structure. Though MIS LED has developed for many years by our group, the detailed light emission mechanism is still unclear and has a dispute. One of the main disputations is the region of the light emission. At the negative bias, the electron tunnels from the metal gate to the p- type semiconductor. After the relaxation to the conduction band of the semiconductor, electron can recombine with holes, which accumulated by the gate bias, and emit the infrared. Our previous work [9] used the strained-Si tunneling diodes to prove that the electron-hole plasma recombination occurs at the thin accumulation layer (several nanometers from the interface). In this work, different Si/SiGe/Si structures MIS LED were done and investigated to verify the light emission region. The energy band of semiconductor under the operation voltage and carrier concentration are also simulated by the commercial tool. It can find that the carrier concentration of the tunneling electron and the doping in the Si semiconductor neutral region limit the light-emitting region to the insulator/Si semiconductor interface.

2. General Instructions

Three different Si/SiGe/Si structures (Fig. 1) used in this work are directly grown on p-type Si (100) substrate with the resistivity of 15-25 $\Omega-cm$ at 525 °C by the ultra-high-vacuum chemical vapor deposition (UHVCVD) using a GeH_4 precursor and a He carrier gas. A different Si-cap layer is succeeded and grown on the top of SiGe layer to form the Si/SiGe QW. The cross sectional and plan-view transmission electron microscope (TEM) images of the SiGe layer with Si-cap layer are examined. It shows that no apparent defect or dislocation in the cross sectional and plane-view TEM image. The 2 nm tunneling oxide is grown on the Si/SiGe QW structure by the liquid phase deposition (LPD) process at 50 ℃ [10]. The indium-tin-oxide (ITO) as a gate electrode with the circular area of 8.85×10^{-2} cm^2 defined by the shadow mask is deposited by sputtering in Ar and O_2 ambient at 20 mTorr. Al was deposited on the backside of the Si substrate as the other electrode of the MIS tunneling diode. Due to the traps in LPD oxide, the trap-assistant tunneling current is dominant in the gate current. At the negative gate bias, the tunneling electron from the gate electrode can have radiative recombination with holes in the Si/SiGe/Si semiconductor structure. The momentum conservation required by the indirect band gap can be achieved by surface roughness scattering, localized holes, and phonons scattering [11,12]. The experimental setup for measuring the EL spectra can refer to Ref. 9. Two InGaAs detectors with different detection region of wavelength are used to detect the ~ 1.1 μm Si and ~ 1.6 μm SiGe signal, respectively. The apparent energy gaps can be extracted by the electron-hole-plasma recombine model [5].

Fig. 2 shows Raman spectra of three Si/SiGe/Si structures and the bulk Ge excited by the 488 nm laser. As compared with the bulk Ge (curve 4 in Fig. 2), the Raman shift of Ge-Ge phonon frequency ($\Delta\omega_{Ge-Ge}$) of the SiGe layer with respect to the bulk Ge peak can be determined (~ 2.1 cm^{-1}). Using the Raman shift of Ge-Ge phonon of the Si/SiGe/Si structure, the Ge concentration is found to be ~ 60%. The similar Raman Spectra of three Si/SiGe/Si structures used in this work indicates that the SiGe concentration and stress level are almost the same in these samples, even if the thickness of Si cap on the epi-SiGe layer are different. Note that the absorption length of the laser excitation (wavelength = 488 nm) is about 0.5 μm. The obvious/clear Raman signal also indicates the quality of Si/SiGe/Si sample is good, which is very important for the light emission in MIS LED.



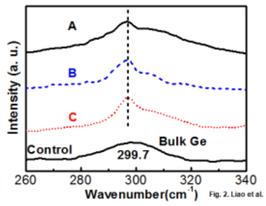


Fig. 1 The schematic diagram of the SiGe QW MIS LED device structures.

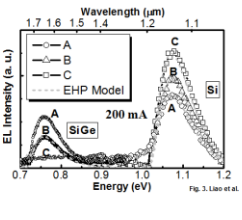
Fig. 2 The Raman spectra of SiGe QW layer with different Si cap thickness.

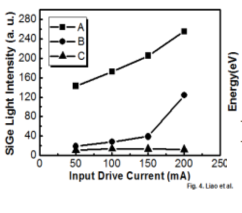
Fig. 3 shows electroluminescence (EL) spectra at different temperatures from the SiGe QW MIS LED with different structures. The drive current is 200 mA at the gate voltage of -4 V. The electron-hole-plasma (EHP) recombination model is used to fit the EL spectra, using the following expression:

$$I(h\nu)=I_0\int_0^{h\nu-E_{g,EL}} dED_e(E)D_h(h\nu-E_{g,EL}-E)\times f_e(E,F_e,T)\,f_h(h\nu-E_{g,EL}-E,F_h,T)$$

where D_e and D_h are the densities of states of electrons and holes, respectively, F_e and F_h are the respective quasi-Fermi energies, hν is the energy of photon emitted, T is the measurement temperature, $E_{g,EL}$ is the bandgap obtained by the EL measurement, and f are the Fermi-Dirac distribution. The apparent energy gaps can be extracted by the EHP model for the spectra [5]. The ~1.1 μm and ~1.6 μm light emission mainly comes from Si and SiGe, respectively, due to the band gap energy of the Si and SiGe. For the ~1.6 μm light emission from the SiGe structure, we can find that it only can be observed in the thin Si cap devices (Sample A and Sample B) with the 200 mA input current. In the thin Si cap device, the electrons tunnel from the metal to the semiconductor, relax to the conduction band of the semiconductor, and recombine with the holes, accumulated in the insulator/Si cap/SiGe region to emit the ~1.6 μm infrared. However, no any ~1.6 μm light signal can be detected in the thicker Si cap QW MIS LED device (Sample C), due to the less-drift and limited electrons can reach to the SiGe region with the thicker Si cap. The electron in Sample C only can recombine with holes in the surface Si cap to emit ~1.1 μm Si infrared. This important experiment result indicates that the light emission region of the MIS LED is mainly from the semiconductor's surface, not the neutral region in the semiconductor sub. On the other hand, the ~1.1 μm Si light emission can be observed in these three samples (A, B, and C) with different Si cap thickness. It is because that the tunneling electrons recombine with the accumulated holes near the insulator/Si cap interface, no matter what the sample (Si cap thickness) we used. This result double confirms the above conclusion that the light emission mainly come from the top insulator/semiconductor interface.

Fig. 4 shows the drive current dependence of the integrated EL intensity for the 1.6 μm emission from the Si/SiGe/Si structures MIS LED. As discussed above, in the thicker Si cap device (Sample C), No ~1.6 μm light emission from SiGe can be observed at arbitrary input driving current. For Sample A (Thin Si cap on SiGe), the emission intensity from the SiGe has a relatively liner dependence on the driving current, similar to our previously reported results [8]. The most interesting phenomenon, which is worthy of our attention, is the relationship between the light emission intensity and input driving current in Sample B. At the low driving current, no ~ 1.6 μm light emission can be detected, due to the less electrons pass through the insulator and Si cap to reach the conduction band of SiGe layer. At the large driving current (>160 meV), the electrons can be drove and reach to the deeper SiGe layer region. After that, the electron has the probability to combine with the holes to emit the ~ 1.6 μm infrared.





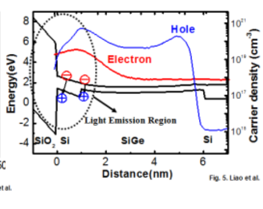


Fig. 3 The EL spectra from Si/SiGe/Si QW tunneling diodes.
Fig. 4 The drive current dependence of integrated EL intensity.
Fig. 5 The energy band diagram of SiGe QW MIS LED.

The detailed energy band diagram and electron/hole carrier concentration (Fig. 5) are also simulated by the quantum mechanical simulation at the accumulation bias, using the commercial simulation tool. The Schroedinger model, Vandort quantum correction model, and QW subband model are involved in this simulation. The hole concentration of the SiGe QW structure at the accumulation bias is mainly located in the insulator/Si interface and SiGe QW layer. The injected electron tunnels from the metal gate to the insulator/Si interface and drift to the semiconductor neutral region. The maximum concentration of the electron carrier is at the insulator/semiconductor interface. Compared with the experiment and simulation results, we can find that the tunneling electrons play an important role on the light emission mechanism. The light emission region in MIS LED is near the insulator/Si interface, where has the maximum electron and hole carrier concentration density. With the larger driving current under the larger bias voltage, the electron has more energy to tunnel through the insulator and drift into the semiconductor neutral region deeply. This will help expand the light-emission region in the semiconductor (Sample B in Fig. 4).

3. Conclusions

The light emission mechanism and region of MIS LED is investigated by different Si/SiGe/Si structures. It shows that the infrared emission is mainly located at insulator/semiconductor interface. The tunneling electron at the accumulated gate bias plays the main role on the light emission and limits the light emission region. At the larger driving voltage, the tunneling electron can be drifted in the semiconductor deeply and the light emission region can also be expanded. The accurate semiconductor simulation model is also provided to understand the light emission mechanism fully.

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