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Novel Electronic and Optical Processes in $Ge_{1-x}Sn_x$ Alloy Based Electronic and Photonic Devices

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ABSTRACT

$Ge_{1-x}Sn_x$ (x>0.08) becomes a direct gap semiconductor with its zone centre Γ valley lower in energy than the four-fold degenerate L valleys. We present our results of electron mobility enhancement, high threshold current density for lasers, novel detector using hetero-phototransistors and low excitonic binding energy in GeSn Quantum Wells unsuitable for modulators.

1. Introduction

The indirect nature of the band gap in Si, Ge and their alloys makes the Gr. IV semiconductors poor light emitter. The absence of linear electro-optic effect also limits the bandwidth of modulators using these materials. The realization of electronic-photonic ICs on Si platform using mature CMOS technology thus is a dream project even today [1-3].

The successful growth of $Ge_{1-x}Sn_x$ alloy on Si and direct gap for x > 0.08 over the last two decades offer solution for the above problems. Brisk activities in realizing field effect transistors, lasers, detectors and modulators have been undertaken.

The present paper aims at describing briefly basic properties of the alloy and the development of electronic and photonic devices. As the indirect L valleys are energetically close to the lower direct Γ valley, electron occupancy in both the valleys poses a problem for obtaining high electron mobility and efficient laser operation. Further, the reduced fundamental gap in the alloy allows operation mainly in MWIR region. On the other hand, hetero-phototransistors (HPTs) using the alloys can compete with InP based detectors at C band.

The main focus of the paper is to present the work of the authors and their team on basic electronic and photonic properties of the alloy relevant for device operation and optimization.

2. Enhanced Electron Mobility

Carrier mobility in a semiconductor and diffusion constant determine the speed of operation of devices, like field effect transistors and bandwidth of transistors and photonic devices. As the electron effective mass in Γ valley is significantly lower than that in higher L valleys, enhanced mobility is expected. However, the separation of the Γ and L valleys in Ge is 140 meV only and varies in the unstrained or strained alloys. Therefore, both the valleys are occupied by electrons and mobility may not be enhanced as expected.

We have made a series of investigations about mobility including acoustic, optical and intervalley phonon, alloy and impurity scatterings for both non-degenerate and degenerate statistics [4-.6] For non degenerate case, mobilty in alloy is 10^5 cm^2/V.s, as compared to 3900 cm^2/V.s in pure Ge. However for high doping needed for device operation such a high value is not achieved. In fact, realistic calculation of mobility has been performed by our group only. Our recent result on highly doped alloy for degeneracy with inclusion of electron-electron scattering gives values in complete agreement with experimental values for low alloy content (~0,02) as well as for x = 0.12 [6].

3. Laser Operation

The direct-gap nature of the alloy prompts a number of workers to investigate laser operation using the alloys, as the alloy can be grown on Si platform, has CMOS compatibility thus leading to the monolithic electronics-photonics integration [7].

For use in communication networks, the emitters should operate continuously at room temperature and must be electrically pumped. Though a number of reports appeared in the literature, none of the devices has met all the criteria and development of such a laser poses a challenge. In addition, the threshold current density shows a very high value.

The operation of laser depends on creation of excess electron-hole pairs by either electrical or optical pumping. This makes the carriers degenerate to follow Fermi Dirac statistics.

We have calculated the sharing of electrons between Γ and L valleys under heavy injection. As the density-of-states effective mass in L valleys is about 100 times larger than that in Γ valley, the non-radiative recombination of electrons in L valleys play a significant role [8]. In order to compensate the loss, the gain is to be increased demanding more injection into the Γ valley, thereby putting the threshold current density at a premium. Increase of x places L valleys at a higher energy, decreases electron density and may yield lower threshold current density. However, the fundamental gap decreases making non-radiative Auger recombination rate extremely high to increase the loss.

4. Hetero Photo Transistors

The detection of optical signals is usually made by p-i-n or Avalanche Photodetectors (APDs). We have worked with the p-i-n structures [9]. However, in the area of detectors, our contribution, for the first time in the literature [10,11], lies in analyzing the performance of Heterojunction Photo Transistors (HPTs). These detectors have internal gain due to transistor action, but is free from excess noise due to random nature of avalanche multiplication process in APDs.

We have solved continuity equation in Ge/GeSn HPTs grown on Si platform to obtain the I-V characteristics, gain, bandwidth and signal-to-noise ratio. Our results indicate significant improvement of the parameters in comparison the existing InGaAs APDs grown on InP [10-14].

5. Excitonic Absorption and Modulators

Excitons are bound electron-hole pair, the binding being due to Coulomb interaction. In Quantum Wells and Quantum Dots, excitons possess large binding energy at room temperature. Application of an electric field changes the absorption spectra. This effect called Quantum Confined Stark Effect (QCSE) is exploited in III-V compounds and alloys to realizes modulators for use in fibre optic links [2,3].

Our investigation for Si/GeSn/Ge QWs shows very low binding energy and therefore obtaining similar modulators in the alloy via QCSE is a remote possibility [15]. We have worked on alternative modulators based on Franz- Keldysh effect.

6. References

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