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Temperature dependent electroluminescence from GeSn heterojunction light emitting diode on Si substrate

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Abstract

GeSn on Si light emitting diode (LED) is investigated under different temperature ranged from 20K to 150K. We obtained the NP and TO replicas. The relationship between band gap energy and temperature is conformed to the Varshni's empirical expression, and theα parameter of GeSn is larger than the α of Ge (4.77×10^{-4}).

1. Introduction

In the past few decades, Si electronic devices have developed rapidly following "Moore's law" with the feature size shrinking to the physical limit. Moreover, besides "Moore's law", Si-based semiconductor materials have been investigated for "more than Moore" applications such as optoelectronic devices, as known as Si photonics. Ge, as a group IV material which is compatible with Si, has been integrated on Si photonics to compensate the inefficient optical properties of Si. Although Ge is also an indirect-bandgap material, it has a ~0.85 eV gap at Γ band (direct). There are several methods to modify the band diagram of Ge so that to increase its luminescence emission probability. By doping high dose of n-type dopant into tensile strained Ge, the bandgap is decreased, which leads to an increase of direct transition [1]. However, using this material on light emitting diodes (LEDs), the threshold density is extremely high [2]. By alloying Ge with Sn, the difference in energy between the Γ band (direct) and L band (indirect) is decreased, and the theoretical transition from indirect bandgap to direct band gap happens when the Sn concentration is about ~6% to 10% [3,4].

In this work, we demonstrate a Ge/GeSn/Ge p-i-n light emitting diode, and show its electroluminescence (EL) properties at different temperature. We have observed the no phonon (NP) and transverse optical (TO) phonon assisted emission peaks. The relation between bandgap and temperature is conformed to the Varshni's empirical expression.

2. Experiment

The diode is grown by a solid source molecular beam epitaxy (MBE) using the low temperature growth technique [5]. The substrate of the structure is an n-type Si (001) wafer, and the structure consists of: (a) high-temperature (HT) Si buffer layer of 30 nm, (b) low-temperature (LT) Si buffer layer of 50 nm, (c) LT Ge buffer layer of 90 nm, (d) HT Ge buffer layer of 80 nm, (e) n-type Ge layer doped with Sb of 250 nm, (f) undoped Ge spacer of 10 nm, (g) undoped GeSn layer of 160 nm, (h) undoped Ge space of 10 nm, (i) p-type Ge layer doped with B of 30 nm. After the growth of buffer layers (a) to (c), the sample is *in-situ* annealed at 800 °C for 15 min. Cross-sectional transmission electron microscopy (XTEM) was used to observe the thickness, and X-ray diffraction (XRD) was used to probe the crystal quality and Sn composition. After establishing the epitaxy properties, the sample was fabricated into a device, whose structure is shown in Fig 1. EL measurement was performed at different temperature, cooled by a close-cycle cryostat, with injection current density of 100 mA/cm^2, and the spectra was detected with an InGaAs

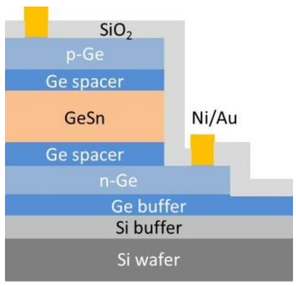

Fig. 1 Schematic view of cross section of the GeSn LED.

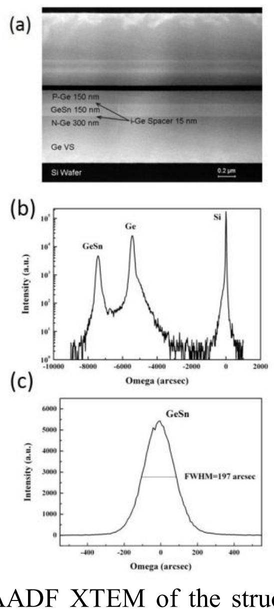

Fig. 2 (a) HAADF XTEM of the structure with thickness marked on it, (b) XRD (004) scan, (c) XRD rocking curve of the GeSn peak.

detector operating at wavelength range of 1100 to 2200 nm.

3. Results and Discussions

The structural properties are measured by several methods and are shown in Fig. 2. Fig. 2 (a) is the high-angle annular dark field (HAADF) XTEM scanning of the structure with layer thickness marked on it. The (004) ω-2θ scanning of XRD shows three peaks: Si, Ge, GeSn, as shown in Fig. 2 (b). The Sn composition is then derived to be 5.1%. The XRD double-crystal rocking curve of GeSn peak is figured in Fig. 2 (c) and shows that the full width at half-maximum (FWHM) is 197 arcsec, which indicates that the defect density in the GeSn layer is $6 \times 10^7\ cm^{-2}$.

The EL spectra measured under various temperatures are shown in Fig. 3 (a). There are three different features observed in this figure: (1) At low temperature as 25K, there is only one peak observed at 0.633 eV, and the peak is red-shifted with the increasing temperature as marked with dashed line; (2) after 50K, a signal in around 0.55 eV is observed, as marked with the solid line.; (3) when the temperature is higher than 100K, a new feature is observed at around ~0.57 eV, as marked with the arrows.

For observation (1), we can determine this feature as the no-phonon (NP) emission of GeSn. In ref. [6], Y. P. Varshni provided an important empirical expression of temperature dependence of energy band gap, named Varshni's expression:

$$E_g(\mathrm{T}) = E_g(0) - \frac{\alpha \cdot T^2}{T+\beta} \qquad (1),$$

where $E_g(0)$, α and β are material constants. For bulk Germanium, α and β are 4.77×10^{-4} and 235, respectively. Fig 3 (b) shows the experimental (GeSn) and theoretical (Ge) relationship between temperature and band gap. The difference between the two curves is caused by the different parameters between Ge and GeSn. The drop in NP energy gap is faster for GeSn than Ge, and this indicates that the α of GeSn is larger. With the increasing temperature, the NP peak is weakened because the phonon-assistant emissions might dominate at higher temperature. For observation (2),

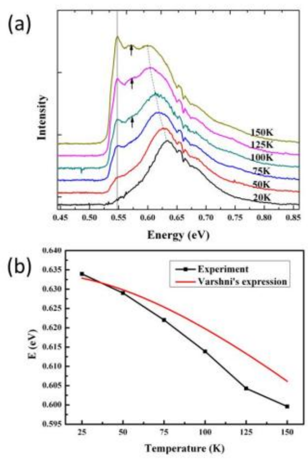

Fig. 3 (a) Emission spectra at temperatures ranged from 20K to 150K, (b) the experimental and theoretical relationship between temperature and band gap.

the signal appears at the same position at every higher temperature, and increases in intensity with the higher temperature. Therefore, we consider the signal is from the defects in the VS. For the observation (3), we find a new feature in the spectra at temperatures above 100K. In Ge system [7], the NP and TO phonon assistant emission differ 36 meV. Although the exact peak position in Fig. 3 (a) is not resolvable, we can still determine it as the TO phonon assistant emission through the energy difference of about 30 meV.

3. Conclusions

Temperature dependent EL of GeSn LED is demonstrated. NP and TO replicas are obtained, and the NP replica is red-shifted with the increasing temperature. The relation between bandgap and temperature is conformed to the Varshni's empirical expression, and the α parameter of GeSn is larger than the α of Ge (4.77×10^{-4}).

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