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Analysis of light emission performance of pseudoheterostructure diode based on germanium micro-bridge

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ABSTRACT

We present an electrically driven pseudoheterostructure diode based on germanium micro-bridge structure, and investigate the electrical transport, internal quantum efficiency and transparency current density of the diode. The effects of injected carrier density and uniaxial tensile strain on intervalence band absorption is also discussed. The injected carrier is well confined in the diode with uniaxial strain around 4%. An internal quantum efficiency around 9% and transparency current density of 5.8kA/cm^2 can be obtained with doping density of 5×10^{18}cm^{-3} and transparency carrier density of 2×10^{18}cm^{-3} when uniaxial tensile strain is 4%. The result indicates the pseudoheterostructure diode based on the Ge micro-bridge can be used to realize an efficient electrically driven Si-based light emission source.

1. Introduction

The efficient light source has long been a crucial and challenging issue for silicon photonics. It is well known that silicon is an indirect bandgap material, which makes it unsuitable for light emission. Recently, the tensile-strained and heavy n-doped Ge attracts intense attention [1]. Although Ge is also an indirect bandgap material, its indirect bandgap edge is only 136 meV larger than the direct bandgap, while the energy difference of the indirect-direct bandgap is more than 2 eV for Si. Moreover, Ge is a Complementary Metal-Oxide-Semiconductor (CMOS) technology compatible material whose energy difference between the indirect and direct bandgap can be reduced by tensile strain. It has been demonstrated that germanium will become a direct bandgap material when the biaxial tensile strain reaches 1.7% or 2.2% [1,2]. On the other hand, n-type doping can also improve the electron occupation probability of Γ valley. The combination of the low biaxial tensile strain and doping will enhance the direct bandgap radiative recombination of Ge as demonstrated in [1]. The influence of the biaxial tensile strain and doping density on transparency current density in Si/Ge/Si heterojunction has also been studied, and these researches predict that a large tensile strain will remarkably reduce the threshold current density [3,4]. However, only 0.25% biaxial tensile strain induced by thermal mismatch between Ge and Si can be achieved if there is no extra strain technology utilized. Therefore, it is difficult to further.

increase the biaxial tensile strain to a high level, implying that a low threshold current density of the Si/Ge/Si heterojunction is hard to realize. Whereas, it is noteworthy that due to stress redistribution, the micro-bridge structure will produce the uniaxial tensile strain larger than 2% which enhances the light emission efficiency obviously [5–7]. A high-Q cavity based on the micro-bridge structure has also been achieved [8]. Furthermore, as a result of the stress redistribution, the micro-bridge structure will naturally form a pseudoheterostructure diode [9]. Most of the investigations are focused on improving optical pumped light emission efficiency by increasing the uniaxial tensile strain [6,10,11]. The problem whether the micro-bridge structure can be utilized to realize efficient electrically driven Si-based light emission source has rarely been discussed.

In this paper, we investigate the electrical transport, internal quantum efficiency and transparency current density of the pseudoheterostructure diode based on the micro-bridge structure. The strain-induced bandgap, effective mass and mobility are taken into account in the electrical transport simulation of the pseudoheterostructure diode. The 8 band $k{\cdot}p$ method and deformation potential theory are used to calculate the energy shift and the effective mass, followed by the calculation of internal quantum efficiency, optical gain and free carrier absorption. The intervalence band absorption is also discussed. The transparency carrier density we obtained can be finally mapped into the current density through the analysis of electrical transport of pseudoheterostructure diode. An internal quantum efficiency around 9% and transparency current density of 5.8kA/cm^2 can be obtained with doping density of 5×10^{18}cm^{-3} and transparency carrier density of 2×10^{18}cm^{-3} when uniaxial tensile strain is 4%. The result indicates the Ge micro-bridge can be utilized to realize an efficient electrically driven Si-based light emission source.

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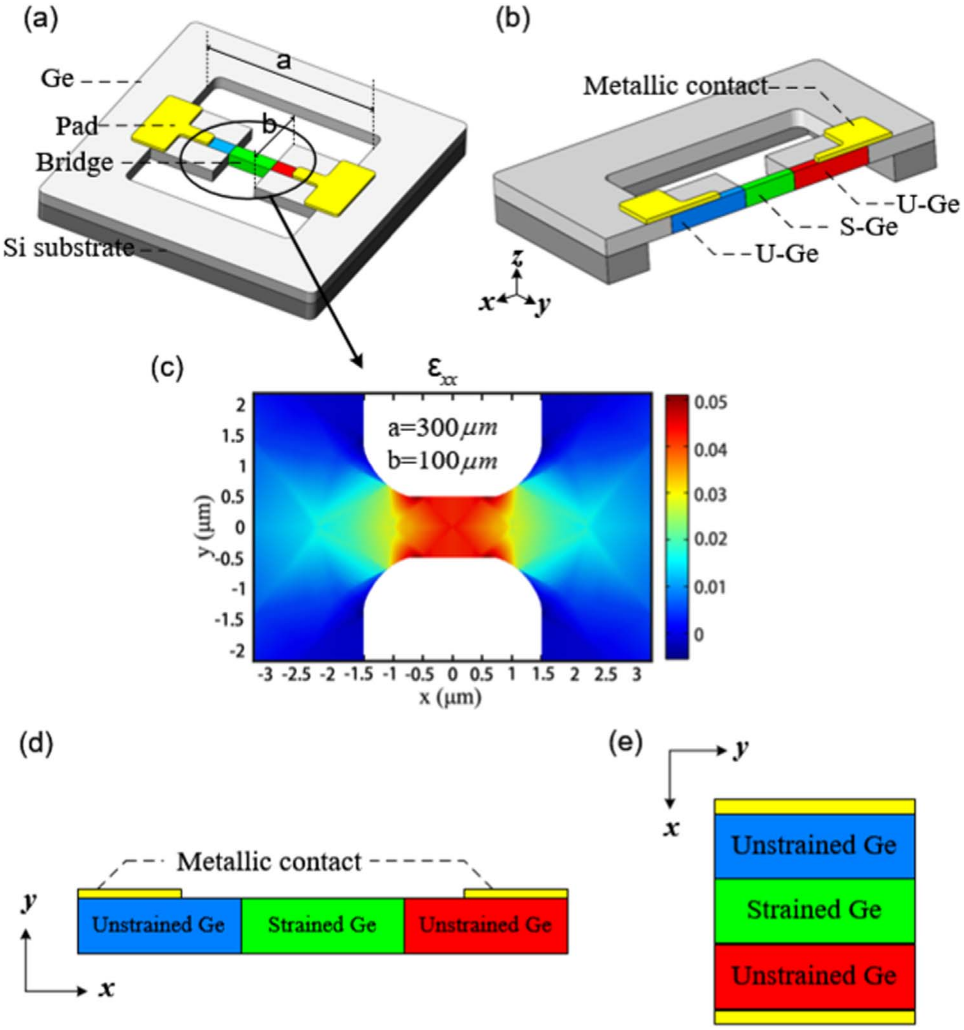

Fig. 1. (a) The micro-bridge structure (not to scale). (b) The cross section of the micro-bridge structure, different color represents different doping, U-Ge and S-Ge represent unstrained Ge and strained Ge. (c) Strain distribution of the micro-bridge structure. (d) Schematic of the pseudoheterostructure diode based on micro-bridge structure. (e) Sandwich-type structure used in simulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Electrical transport in pseudoheterostructure diode

Fig. 1(a) shows the schematic of germanium micro-bridge structure. This structure consists of two pads on both sides and a much narrower bridge in the middle. By using dry etching to define the geometry and then using wet etching to remove the underlying layer, the pads and bridge are suspended and meanwhile the pre-existing thermal strain is released, leading to strain amplification in the bridge region [5]. Finite element Method is used to simulate the strain distribution in the micro-bridge structure. Fig. 1(c) shows the uniaxial tensile strain concentrated in the bridge is about 4%, much larger than that of the two pads. Since tensile strain reduces the bandgap of Ge, the pad/bridge/pad structure forms a pseudoheterostructure diode. The stress redistribution makes the stress in the pad be released to the bridge. Therefore, it can be assumed that the strain on pads can be neglected in the analysis of electrical transport of the pseudoheterostructure diode. Fig. 1(d) shows the schematic of the pseudoheterostructure diode based on micro-bridge structure. In order to facilitate the simulation of the electrical transport, the pseudoheterostructure diode is translated to a sandwich-type structure by rotating the structure shown in Fig. 1(d) and putting the metallic contacts on the top and bottom. Fig. 1(e) shows the pseudoheterostructure diode used in simulation. The top and bottom layers are unstrained Ge, the middle layer is strained Ge. The thickness of each layer is set to be $1\mu m$.

The strain-induced energy of L conduction valley can be expressed as [12].

$$E_{c,L}(k) = E_L + \frac{\hbar^2 k^2}{2m_L} + \delta E_{\varepsilon,L}$$
$$\delta E_{\varepsilon,L} = a_L(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}), \qquad (1)$$

where E_L is the energy of L conduction valley in unstrained Ge,$\hbar$ is Plank's constant,k is the wave vector,m_L is the effective mass of L conduction valley, $\delta E_{\varepsilon,L}$ is the strain-induced energy shift,ε_{xx},ε_{yy},ε_{zz} are the strain components, and the deformation potential a_L is experimentally measured about −1.54 eV [13]. We assume that the principal stress direction is along the x direction, thus the relationship among ε_{xx},ε_{yy},ε_{zz} can be described by $\varepsilon_{yy} = \varepsilon_{zz} = -C_{12}/(C_{11} + C_{12})\varepsilon_{xx}$. The stiffness matrix elements of Ge are $C_{11} = 12.92$ and $C_{12} = 4.79$ [14].

For the Γ conduction valley and valence band, the 8 band $k{\cdot}p$ method is used to model the strain dependent band structure [15]. The energy shifts of Γ conduction valley, heavy hole (HH) band and light hole (LH) band can be obtained by this analysis process.

Since the band structures of the conduction and valence band near the Brillouin zone center have been achieved, the strain dependent effective masses,m_Γ, m_{HH},m_{LH} can be deduced by the following expression [12].

$$m_j = \left(\frac{\hbar^2}{2}\right)\left(\frac{1}{2\pi\sqrt{E_{th}}}\left.\frac{dV}{dE}\right|_{E=E_{th}}\right)_j^{2/3}, \qquad (2)$$