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Enhancement of Direct Band Gap Emission from Germanium by Metal-Oxide-Semiconductor Structure

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Abstract

An idea of enhancing the direct band gap emission from Germanium (Ge) with the sub-band engineering utilizing metal-oxide-semiconductor (MOS) structure is proposed and experimentally demonstrated. Ultra-high carrier concentration can be theoretically achieved through tuning the Fermi level on the surface of *n*-type Ge towards the direct *Γ*-valley by the electric field. The significant enhancement of direct band gap photoluminescence is observed from the Ge MOS structure with high-quality gate stacks of $Al_2O_3/GeO_x/Ge$ as well as a transparent gate of graphene, applied with low positive gate voltages.

1. Introduction

To achieve the high-efficiency direct band gap emission from Germanium (Ge), sufficient electrons must occupy the direct band valley (*Γ*-valley), which means that the Fermi level should be raised close to or even above the *Γ*-valley [1]. The most widely studied method for tuning the Fermi level is heavy doping while it is quite difficult to achieve high doping concentrations in Ge as well-known [2]. On the other hand, in metal-oxide-semiconductor (MOS) structures, the Fermi level of the semiconductor surface could be tuned by applying a voltage at the metal electrode. Under a positive voltage, the *n*-type semiconductor surface is under the so-called accumulation region and the Fermi level could be raised much closer to or even enter into the conduction band. In the case of *n*-type Ge, since the energy difference between *L*-valley, the bottom valley of the conduction band of Ge, and *Γ*-valley is only 136 meV, the electron occupancy in *Γ*-valley of the Ge surface might be enhanced by the metal-oxide-germanium (Ge) MOS structure when the structure is under the accumulation region. As a result, the efficiency of direct band gap light emission from Ge could be improved.

Therefore, in this study, we propose a novel method for enhancing the direct band gap light emission from Ge using the MOS structure and experimentally prove the effectiveness of this new method. Both the theoretical analysis and experimental results indicate that the method is very effective for enhancing the direct band light emission efficiency and could be promising for fabricating high-performance Ge light emitting devices (LEDs) and lasers.

2. Theoretical Model

Fig. 1 illustrates the novel idea of sub-band engineering by using Ge MOS structure for raising electron population in *Γ*-valley. In the *n*-Ge MOS structure, a positive bias on the gate could attract electrons to the Ge surface, resulting in the formation of an accumulation layer with high electron density [3]. Fig. 2a shows that the surface charge density varies exponentially with the band bending in the accumulation layer. On the other hand, as shown in Fig. 2b that a high-*k* gate dielectric helps attract higher density surface charges. For example, at a fixed N_D (5×10^{17} cm^{-3}) and d_0 (5 nm), when the positive gate bias is 4 V, the surface charge density is 4.7×10^{-6}, 1.0×10^{-5} and 1.3×10^{-5} C/cm^2 for ε_{r0} (i.e. *k*) value of 7, 15, 20, respectively. Concerning that the thickness of the accumulation layer is comparable to a Debye length (λ_n=6.8 nm when $N_D=5\times10^{17}$ cm^{-3} in Ge), the corresponding equivalent doping concentration is 4.3×10^{19}, 9.1×10^{19}, and 1.2×10^{20} cm^{-3}, respectively. Fig. 2c further reveals that the gate bias could introduce much larger band bending in the case of high-*k* gate dielectrics. In other words, with high-*k* dielectrics, the Fermi level could be raised above *L*-valley more easily. It would be also achievable for the Fermi level being raised up towards or above *Γ*-valley. For example, at fixed N_D (5×10^{17} cm^{-3}) and d_0 (5 nm), when Fermi level reaches the bottom of *Γ*-valley, the gate voltages are 4.2, 2.1 and 1.6 V, corresponding to *k* values of 7, 15 and 20, respectively.

3. Device fabrication

Light emitting devices by using *n*-Ge MOS structure with graphene as the transparent gate were designed and fabricated, which enables the surface emitting from Ge MOS structure instead of the edge emitting or scattering from the periphery of the gate area. After the pre-cleaning of Ge wafers, $Al_2O_3/GeO_x/Ge$ gate stacks were formed in-situ by the 2-step atomic layer deposition (ALD) using ozone post oxidation (OPO) and post deposition annealing (PDA) [4]. Then, a chemical-vapor-deposited (CVD) monolayer graphene was transferred onto the Al_2O_3 layer by the PMMA supporting technique [5]. Graphene was patterned by the photolithography and etched by the plasma treatment. The gate areas were defined by the photolithography process and the Au/Cr gate electrodes were deposited by thermal evaporation following with lift-off process. The Al back contacts were formed by the thermal evaporation.

4. Results and Discussion

Fig. 3a shows the 3D schematic diagram of the *n*-Ge MOS structure with the graphene as a transparent gate and GeO_x as an interface layer (IL). Fig. 3b and 3c are the cross-sectional TEM images of the MOS structure. Fig. 4 shows the C-V characteristics of the *n*-Ge MOS capacitors. The Ge MOS structure without the OPO treatment was broken down when the gate voltage is only 1 V. While the Ge MOS structure with the OPO treatment, which owns high quality gate oxide, exhibits excellent C-V characteristics, including well-controlled frequency dispersion and low dissipation factor. It can stand a positive gate voltage of till 2.4 V. The photoluminescence (PL) properties of the *n*-Ge MOS structures with and without OPO treatment were also measured. The sample without the OPO treatment almost shows no enhancement of the PL intensity under a positive gate bias (Fig. 4e). And the OPO treated devices show the obvious enhancement of the PL intensity (Fig. 4f). This is attributable to the much more band bending of the OPO treated device as predicted in the theoretical model above.

5. Conclusions

In this work, we have proposed a new method for achieving high efficiency direct band gap light emission from Ge by utilizing the MOS structure. The experimentally fabricated Ge MOS structures show good light emission performance, indicating the effectiveness of this new method. Therefore, the Fermi level tuning technique by using MOS structures could be promising for future Ge LEDs and lasers applications.

Acknowledgements

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References

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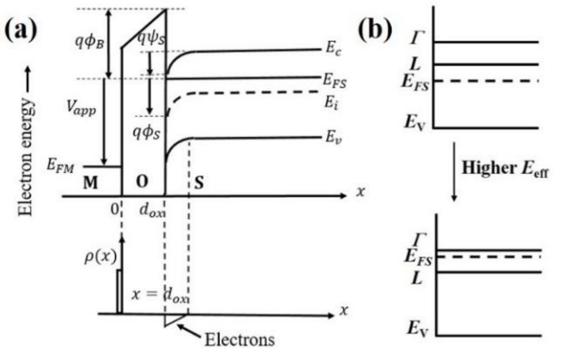

Fig. 1 (a) Energy diagram of the MOS system for *n*-type Ge in accumulation. (b) Schematic illustration of the surface band bending effect on the relative position of Fermi level, *L*-, *Γ*-valley for *n*-Ge in accumulation.

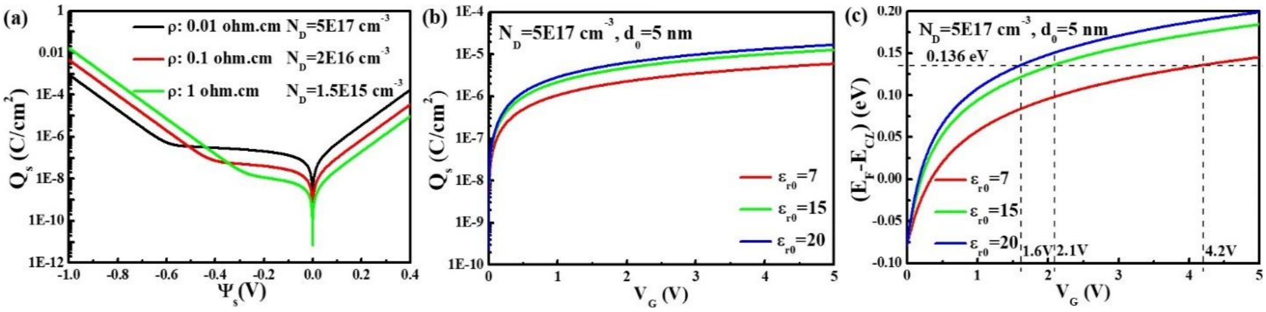

Fig. 2 (a) Calculated surface charge density as a function of Ge surface band bending. (b) Calculated surface charge density, (c) relative position of Fermi level to *L*-, *Γ*-valley as a function of the positive gate voltage for *n*-Ge MOS in accumulation.

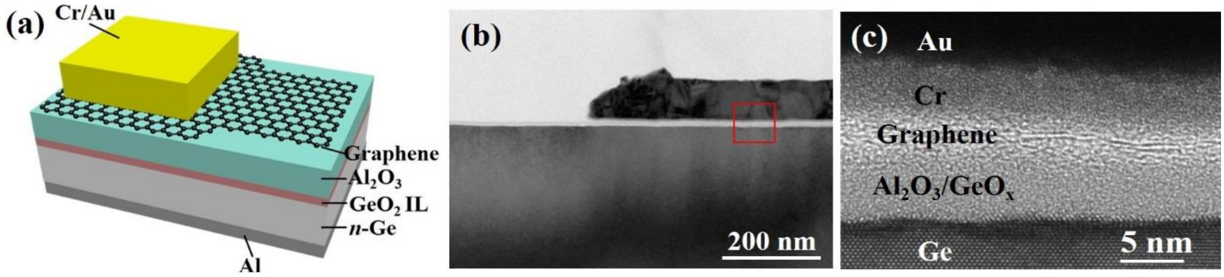

Fig. 3 (a) 3D schematic diagram of the Ge MOS structure with graphene as transparent gate. (b) Cross-sectional TEM image of the MOS structure. (c) HRTEM of the selected area in the red box of (b).

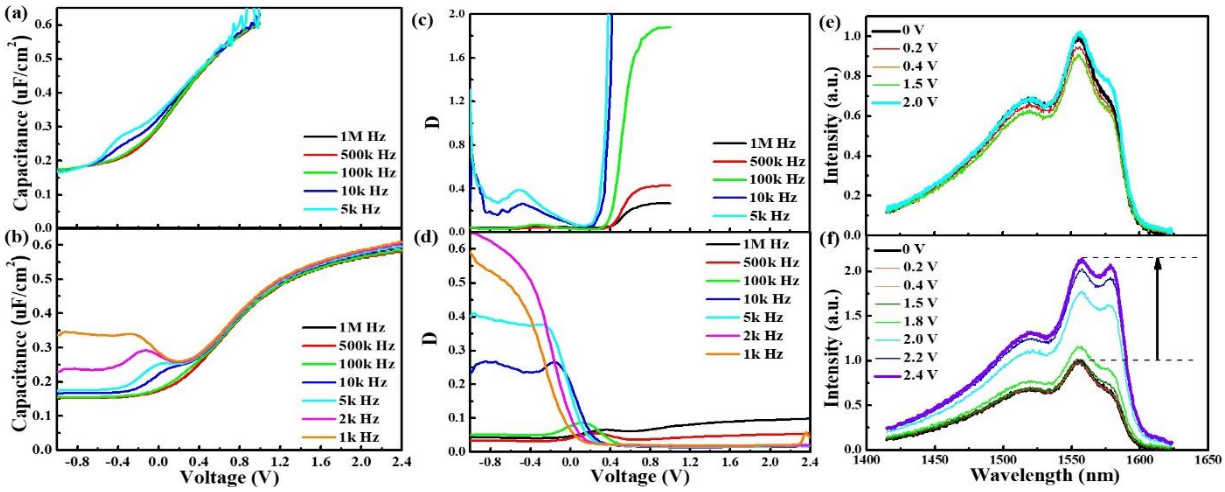

Fig. 4 C-V characteristics and dissipation factor D of the Au/Cr/Graphene/Al_2O_3/GeO_x/*n*-Ge MOS capacitors: (a) (c) poor quality gate oxide, and (b) (d) good quality gate oxide. Under increased positive gate voltage, almost no enhancement of direct band gap PL intensity from the Ge MOS capacitors for (e) poor quality gate oxide, and significant enhancement for (f) good quality gate oxide.