Simulation of impacts of traps on the optical response of a butt-coupled InGaAs photodetector

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Abstract: We studied the impacts of hole traps on the optical response of a butt-coupled $In_{0.53}Ga_{0.47}As$ photodetector. Traps at the $In_{0.53}Ga_{0.47}As/SiO_2$ interface deteriorate quantum efficiency and the two highest cut-off frequencies. Traps at the $In_{0.53}Ga_{0.47}As/Si$ interface improve the lowest cut-off frequency.

1. Introduction

Highly efficient monolithic III-V/Si waveguide-coupled photodetectors (WGPDs) with fast response are favorable for many future applications, such as optical interconnects and quantum information processing. The monolithic integration of III-V materials with Si is fundamentally challenging [1], and interface traps are an inevitable by-product of the fabrication process. Therefore, it is necessary to investigate the impacts of traps on the optical performance of such WGPDs. Here, the studied device is a non-plasmonic butt-coupled p-i-n $In_{0.53}Ga_{0.47}As$ WGPD proposed in our former work [2], with its 3D structure sketched in Fig. 1(a). To gain insights into the effect of defects on device performance, we assume hole-type traps (h-traps) at two different locations: (i) at the bottom $In_{0.53}Ga_{0.47}As/SiO_2$ interface [3] and (ii) at the $In_{0.53}Ga_{0.47}As$/Si-WG interface. The impacts of h-traps on the optical response can be extracted by comparing response curves obtained from a defective and an ideal device.

2. Simulation Methodology

The optical response curve is obtained from coupled 3D opto-electrical simulations. First, the optical generation rate is calculated using *Sentaurus Electromagnetic Solver*. Then we perform electrical transport simulation with *Sentaurus Device*, where the reverse bias is quasi-statically ramped to -2 V. On top of that, an optical AC analysis is performed to calculate the optical response curve, which describes the change of the QE induced by a modulation of the optical generation. Details of the simulation are explained in Ref. [2].

3. Simulation Results

First, for h-traps at $In_{0.53}Ga_{0.47}As/SiO_2$ interfaces, the optical response curves of the ideal and defective device are shown in Fig. 1 (b). The optical response of the ideal device (dark solid curve) has three cut-off frequencies [2]:

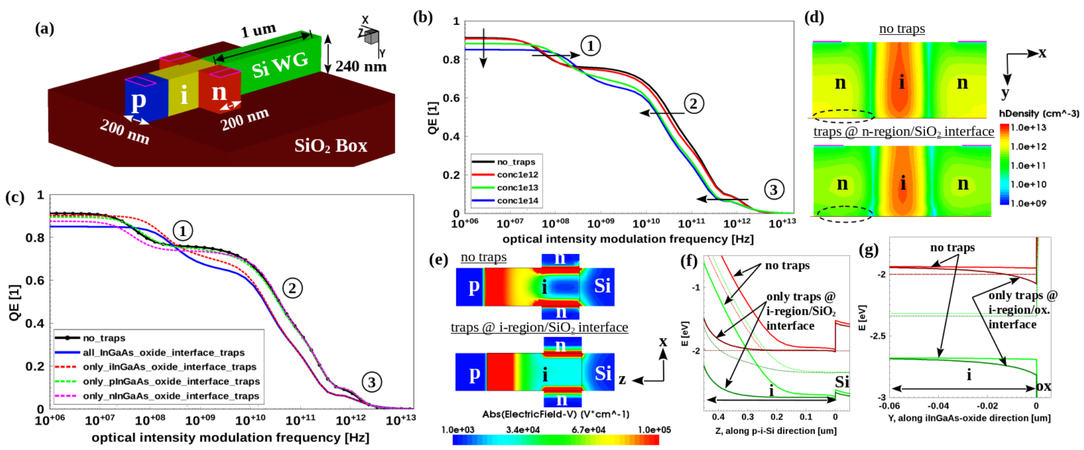

Fig. 1: (a) Sketch of studied device structure. Comparison of optical response curves obtained from an ideal and a defective device with h-traps at (b) all $In_{0.53}Ga_{0.47}As/SiO_2$ interfaces with a concentration of 1e12, 1e13, and 1e14 $cm^{-2}eV^{-1}$, (c) only at the p/i/n-$In_{0.53}Ga_{0.47}As/SiO_2$ interface with a concentration of 1e14 $cm^{-2}eV^{-1}$. (d) Hole density profiles of a device without and with traps at n-$In_{0.53}Ga_{0.47}As/SiO_2$ interface at -2 V. (e), (f)/(g) E-field, band diagrams along p-i-Si/i-SiO_2 direction of a device without and with traps at i-$In_{0.53}Ga_{0.47}As/SiO_2$ interface.

the lowest cut-off is mainly limited by hole diffusion from Si, but also the small electric field (E-field) near the i-region/Si interface, while the middle (highest) cut-off is caused by drift of holes (electrons) in the high-field i-region far from Si. The presence of traps leads to a decrease of quantum efficiency (QE) and the two highest cut-off frequencies, whereas the lowest cut-off frequency slightly increases with rising trap concentration. To figure out the origins of such observations, we perform additional simulations with h-traps (concentration of 1e14 $cm^{-2}eV^{-1}$) only located at the interface between p/i/n-InGaAs and bottom SiO_2 (see Fig. 1 (c)). One can see that the drop of QE (change of cut-off frequencies) is mainly related to h-traps at the interface between n-doped (intrinsic) InGaAs region and bottom SiO_2. Fig. 1 (d) compares the hole density profiles without and with h-traps at the n-InGaAs/SiO_2 interface, showing that the loss of optically generated holes in the n-doped regions causes the deterioration of the QE. To analyze why the cut-off frequencies change, we compare the E-field profiles without and with h-traps at the i-InGaAs/SiO_2 interface (see Fig. 1 (e)). The decrease of the two highest cut-off frequencies is due to the smaller E-field in the i-region far from the interface to Si, caused by the weaker band bending in the presence of such traps (see Fig. 1 (f)). The small increase of the lowest cut-off is related to the slightly enhanced E-field in the i-region near the i-region/Si interface (see Fig. 1 (e)), where the higher field is a consequence of the stronger band bending at the i-region/SiO_2 interface resulting from the assumed h-traps, as shown in Fig. 1 (g).
Next, we study h-traps at the $In_{0.53}Ga_{0.47}As$/Si interface, in particular the section between i-$In_{0.53}Ga_{0.47}As$ and Si-WG which is part of the butt-coupled structure. The comparison of the simulated optical response curves of the ideal and defective device is shown in Fig. 2 (a). It turns out that in the presence of this type of traps, though the QE slightly drops, the lowest cut-off frequency largely improves and the other two highest cut-off frequencies are almost unaffected. Since the lowest cut-off frequency is mainly limited by the slow hole diffusion process near the i-region/Si interface in the ideal device [2], we compare the hole density profiles of the ideal and defective device in this region to find out the reason behind the observed improvement. As one can see in Fig. 2 (b) and (c), the

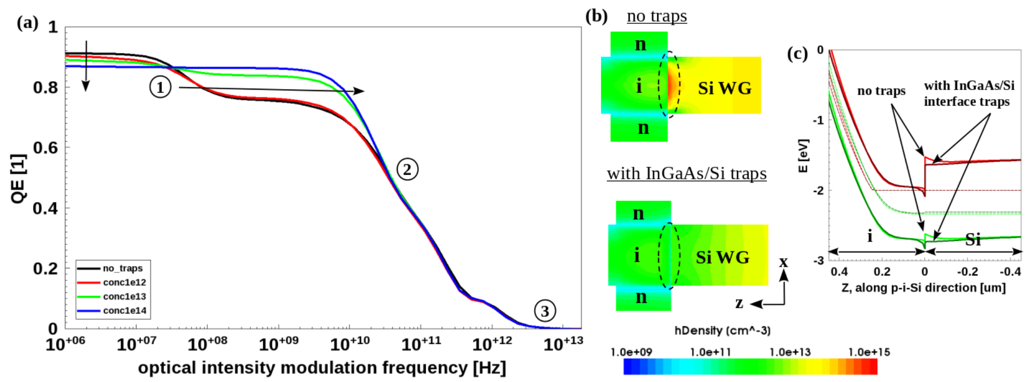

Fig. 2: (a) Comparison of optical response curves obtained from an ideal and a defective device with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interfaces having a concentration of 1e12, 1e13, and 1e14 $cm^{-2}eV^{-1}$. (b)/(c) Comparison of hole density profiles/band diagrams at -2 V obtained from simulations without and with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interface with a concentration of 1e14 $cm^{-2}eV^{-1}$.

hole density gradient near the i-region/Si interface of the ideal device comes from the hole potential well at this interface, which is related to the valence band offset at the i-$In_{0.53}Ga_{0.47}As$/Si interface. However, in presence of the assumed h-traps this density gradient disappears. Thus, the slow hole diffusion process no longer exists in the defective device, and the lowest cut-off frequency becomes higher.

4. Conclusion

In a butt-coupled $In_{0.53}Ga_{0.47}As$ p-i-n photodetector, hole traps at the interfaces between n-doped $In_{0.53}Ga_{0.47}As$ and SiO_2 lead to a drop of the QE due to the loss of optically generated holes there. Hole-type traps at the i-$In_{0.53}Ga_{0.47}As/SiO_2$ weaken (strengthen) the E-field in the i-region far from (close to) the i-region/Si interface, resulting in a decrease of the two highest cut-off frequencies (an increase of the lowest cut-off frequency). Hole traps at the $In_{0.53}Ga_{0.47}As$/Si interface help to improve the lowest cut-off frequency by eliminating the slow hole diffusion process near the i-region/Si interface.

References

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