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# Theoretical study of impacts of traps on the optical response of side-coupled InGaAs waveguide photodetectors

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## ABSTRACT

We study the impact of hole traps on the optical response of Si waveguide-coupled p-i-n $In_{0.53}Ga_{0.47}As$ photodetectors. Compared with the ideal case, a trap density of 1e14 $cm^{-2}eV^{-1}$ at the $In_{0.53}Ga_{0.47}As/SiO_2$ interface reduces the device's quantum efficiency by about 10% and its cut-off frequency by a factor of 2. The drop of the quantum efficiency is mainly caused by interface traps at heavily doped regions, whereas the cut-off frequency degrades due to interface traps at the i-region. Hole traps at the $In_{0.53}Ga_{0.47}As$/Si interface, however, have no effect on the quantum efficiency - only the cut-off frequency drops with increasing trap concentration. Similar impacts of such traps are observed in plasmonic waveguide-coupled photodetectors with a metal strip placed on top of the i-region.

**Keywords:** III-V/Si p-i-n WGPD, interface traps, optical response

## 1. INTRODUCTION

Waveguide-coupled photodetectors (WGPDs) implemented on a III-V/Si platform with small footprint are one of the key components in integrated photonic circuits. For future applications like optical interconnects and quantum information processing, WGPDs with large quantum efficiency (QE) and high cut-off frequency are desirable. While many factors can affect these performance parameters, here we focus on the impact of interface traps, which are an unavoidable side product of the fabrication process. For this purpose, we employ coupled 3D opto-electrical simulations to analyze the optical response of a side-coupled p-i-n $In_{0.53}Ga_{0.47}As$ PD with hole type traps (h-traps) assumed at two different interfaces. The studied devices include a non-plasmonic WGPD and a plasmonic WGPD proposed in our former work,[1] the latter being formed by placing a Ag strip on top of the i-region. The device structures with identical geometry of the $In_{0.53}Ga_{0.47}As$ p/i/n-region are sketched in Fig. 1 (a) and (b). Such WGPDs can be fabricated using template-assisted selective epitaxy method[2] and example devices haven been reported recently in Ref.[3] For the first case, h-traps are assumed to reside at the

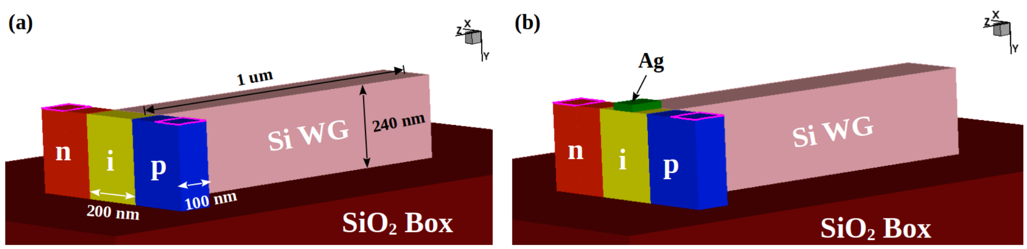


Figure 1. Sketch of studied device: (a) non-plasmonic and (b) plasmonic WGPD. The metal strip on the i-region of the plasmonic device is 80 nm/20 nm/100 nm long in x/y/z direction.

bottom $In_{0.53}Ga_{0.47}As/SiO_2$ interface,[4] whereas they are placed at the $In_{0.53}Ga_{0.47}As$/Si-WG interface for the second case. In both cases the energetic distribution of traps is assumed to be uniform over the band gap of $In_{0.53}Ga_{0.47}As$ (0.74 eV), with Huang-Rhys factor (phonon energy) set to 3 (6 meV) in the barrier tunneling

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model. The trap concentration is varied from 1e12 to 1e14 $cm^{-2}eV^{-1}$ to explore its effect on the optical response. In the following, first the simulation method is described in Sec. 2, then the impacts of h-traps on the optical response of non-plasmonic and plasmonic devices are discussed in Sec. 3.

## 2. SIMULATION METHODOLOGY

The optical response curve is obtained by running two-fold simulations using *Sentaurus TCAD*. First, an optical *Finite-Difference-Time-Domain (FDTD)* simulation is performed using *Sentaurus Electromagnetic Solver*[5] to calculate the optical generation in the device region. Plane-wave excitation is assumed propagating from the end of the Si WG towards the p-i-n region, with wavelength of 1350 nm and intensity of 100 $Wcm^{-2}$. The obtained optical generation profile serves as input for the electrical transport simulation with *Sentaurus Device* based on the *drift-diffusion formalism*,[6] where the reverse bias is quasi-statically ramped to -2 V. On top of that, an optical AC analysis is performed using *Sentaurus Device*[6] to calculate the optical response curve, which describes the change of the QE induced by a modulation of the optical generation. The impacts of h-traps on the optical response can be extracted by comparing response curves obtained from a defective and an ideal device.

## 3. SIMULATION RESULTS

In this section, we discuss the impacts of h-traps at the bottom $In_{0.53}Ga_{0.47}As/SiO_2$ and the $In_{0.53}Ga_{0.47}As$/Si-WG interface, respectively, on the optical response of the studied non-plasmonic and plasmonic WGPD.

### 3.1 Non-plasmonic WGPD

First, for h-traps located at the bottom $In_{0.53}Ga_{0.47}As/SiO_2$ interface, the comparison of the optical response curves of an ideal and a defective device is shown in Fig. 2 (a). One can see that the presence of traps leads to decrease of both QE and cut-off frequency. The degradation becomes stronger as the trap concentration increases from 1e12 to 1e14 $cm^{-2}eV^{-1}$. To figure out the origin of the observed drop of QE and cut-off frequency, we perform additional simulations with h-traps (concentration of 1e14 $cm^{-2}eV^{-1}$) only located at the interface between p/i/i-InGaAs and bottom $SiO_2$. Fig. 2 (b) shows that the drop of QE (cut-off frequency) is mainly related to h-traps at the interface between heavily doped InGaAs region (undoped i-InGaAs region) and bottom $SiO_2$. From the hole density profiles in Fig. 2 (c) it becomes obvious that the presence of h-traps at the p/n-InGaAs and $SiO_2$ interface leads to a lower hole density in regions labeled by the black dashed circles. The loss of optically generated holes in these regions results in a drop of the QE. The decrease of the cut-off frequency in the presence of h-traps at the i-region/$SiO_2$ interface is due to the smaller electric field and the weaker band bending, as seen from the comparison in Figs. 2 (d) and (e). A lower E-field means that the carrier collection process slows down, and, therefore, the cut-off frequency decreases.

Next, we consider h-traps located only at the interface between i-$In_{0.53}Ga_{0.47}As$ and Si-WG, as only the intrinsic region is in contact with Si in a side-coupled structure. The comparison of the simulated optical response curves from an ideal and a defective device is shown in Fig. 3 (a). It turns out that the QE is almost unaffected in this case, while the cut-off frequency decreases with increasing trap concentration. Again, the drop of the cut-off frequency originates from the lower E-field in the i-region in presence of h-traps, as shown by the comparison of E-field profiles in Fig. 3 (b). The corresponding difference in band bending (see Fig. 3 (c)) is similar to the former case.

### 3.2 Plasmonic WGPD

In case of the plasmonic device, the Schottky barrier height (SBH) at the metal/i-region interface is assumed to be either very small or large (0.1 eV or 0.6 eV). This aims to verify whether the influence of h-traps (with an assumed $D_{it}$ of 1e14 $cm^{-2}eV^{-1}$) on the device's optical response changes with different values of the SBH. First, for h-traps located at the bottom $In_{0.53}Ga_{0.47}As/SiO_2$ interface, the simulation results for the plasmonic device are shown in Fig. 4 (a). One can see that the observed impact is similar to the degradation of the non-plasmonic device, i.e. both the QE and the cut-off frequency drop as consequence of the interface traps. Furthermore, this observation holds for both values of the SBH (0.6 eV and 0.1 eV). The reasons behind the drop of QE and cut-off frequency are the same as in the non-plasmonic case, as seen from the comparison of hole density

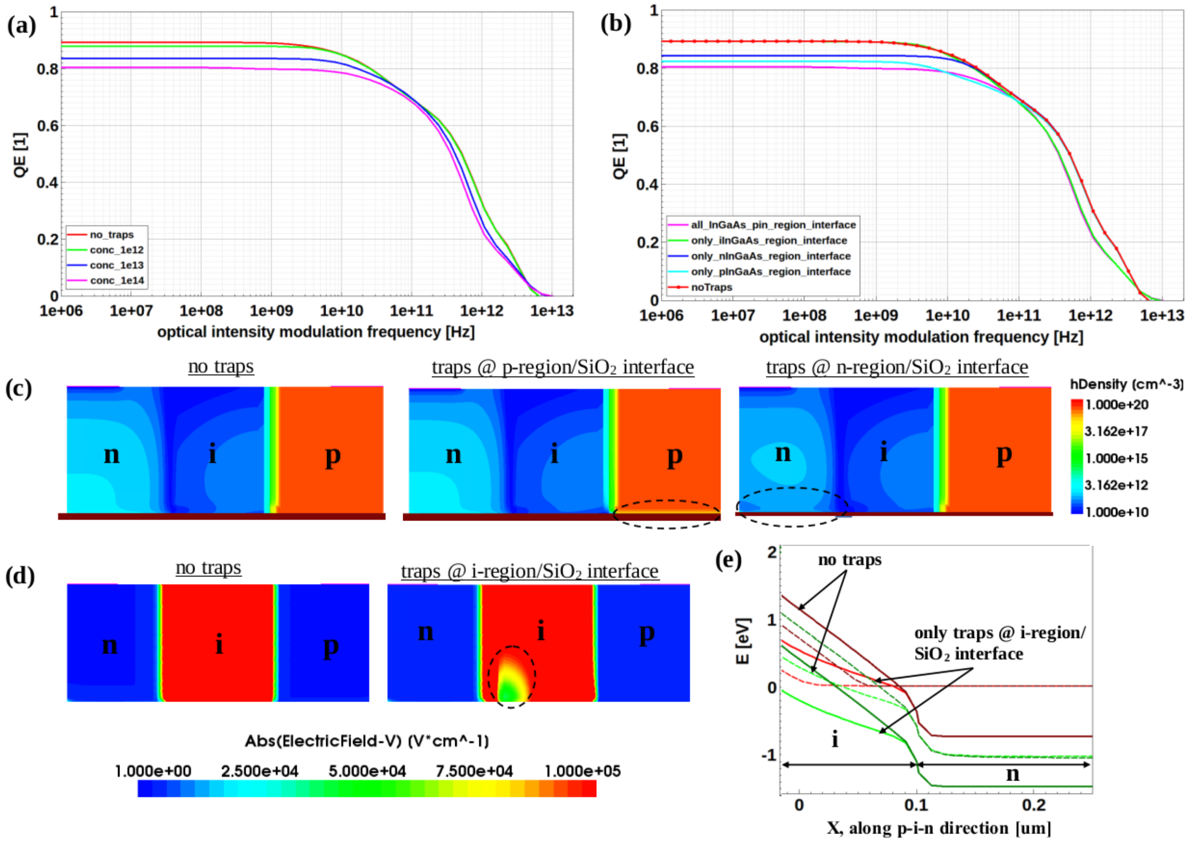


Figure 2. Comparison of optical response curves obtained from an ideal and a defective non-plasmonic device with h-traps at (a) all $In_{0.53}Ga_{0.47}As/SiO_2$ interfaces with a concentration of 1e12, 1e13, and 1e14 $cm^{-2}eV^{-1}$, (b) only at the p/i/n-$In_{0.53}Ga_{0.47}As/SiO_2$ interface with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

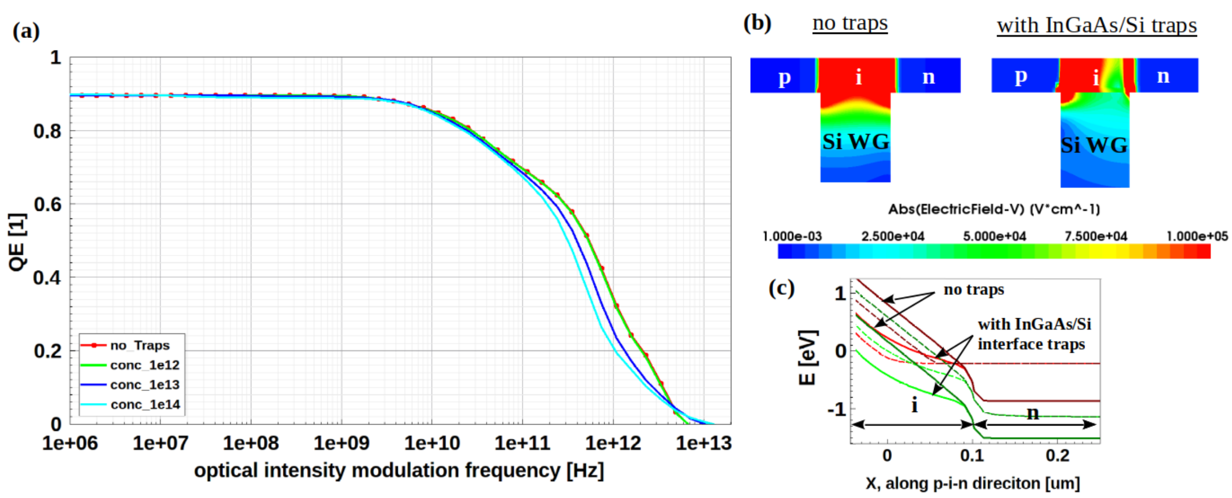


Figure 3. (a) Comparison of optical response curves obtained from an ideal and a defective non-plasmonic device with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interfaces having a concentration of 1e12, 1e13, and 1e14 $cm^{-2}eV^{-1}$. (b)/(c) Comparison of E-field profiles/band diagrams at -2 V obtained from simulations without and with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interface with a concentration of 1e14 $cm^{-2}eV^{-1}$.

and E-field profiles with SBH being 0.1 eV in Fig. 4 (b) and (c) as example. If the h-traps are located at the $In_{0.53}Ga_{0.47}As$/Si-WG interface, they mainly degrade the cut-off frequency for both large and small Schottky barriers, as shown in Fig. 4 (d). This is again related to the decrease of E-field intensity in the i-region caused by the presence of h-traps (see Fig. 4 (e)), which is also similar as in a non-plasmonic device.

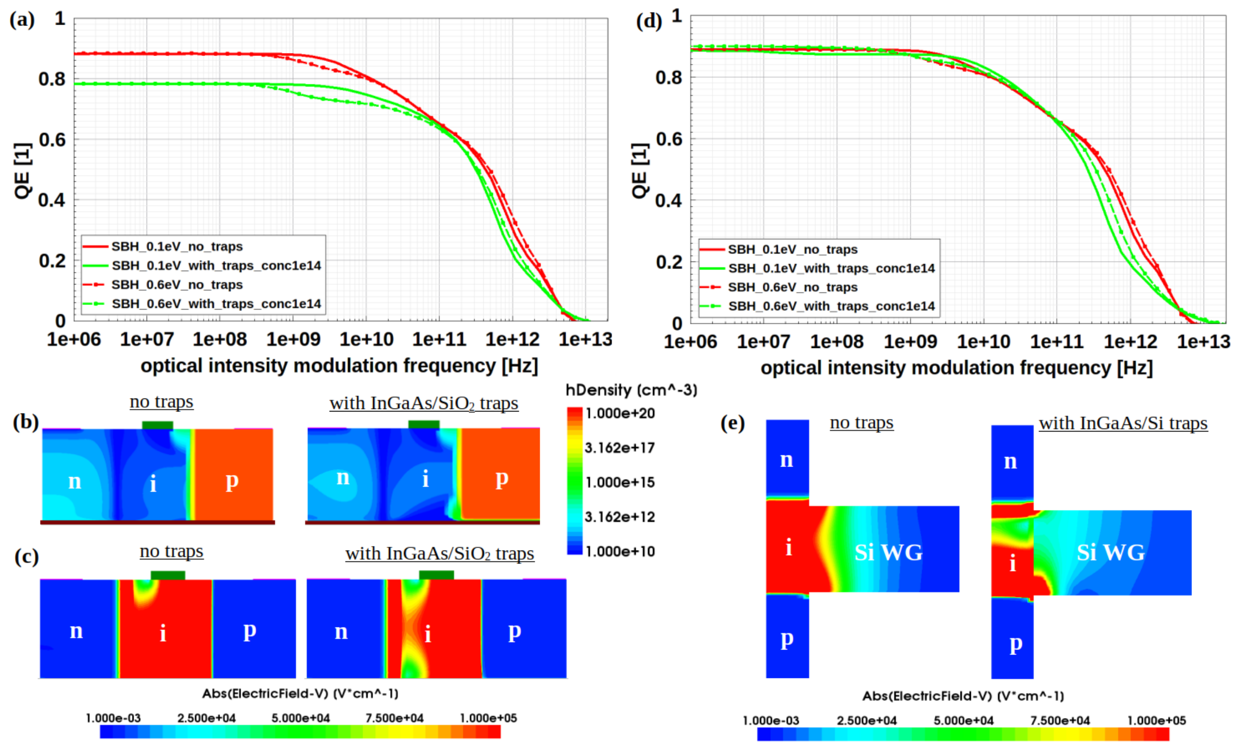


Figure 4. (a) Comparison of optical response curves obtained from an ideal and a defective plasmonic device with h-traps at the $In_{0.53}Ga_{0.47}As/SiO_2$ interfaces with a concentration of 1e14 $cm^{-2}eV^{-1}$. (b)/(c) Comparison of hole density/E-field profiles at -2 V obtained from a plasmonic device (SBH 0.1 eV) without and with h-traps at the $In_{0.53}Ga_{0.47}As/SiO_2$ interface. (d) Comparison of optical response curves obtained from an ideal and a defective plasmonic device with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interface with a concentration of 1e14 $cm^{-2}eV^{-1}$. (e) Comparison of E-field profiles at -2 V obtained from a plasmonic device (SBH 0.1 eV) without and with h-traps at the $In_{0.53}Ga_{0.47}As$/Si-WG interface.

## 4. CONCLUSION

We investigated the impact of hole-type traps at two different interfaces in a p-i-n $In_{0.53}Ga_{0.47}As$ PD with a side-coupled Si WG. Traps at the $In_{0.53}Ga_{0.47}As/SiO_2$ interfaces are shown to deteriorate both quantum efficiency and cut-off frequency. The drop of QE is related to the loss of optically generated holes caused by traps at the p/n-$In_{0.53}Ga_{0.47}As$ and $SiO_2$ interfaces, while the decreased cut-off frequency is due to a downshift of the band edge resulting from the lowered E-field in presence of traps at the i-$In_{0.53}Ga_{0.47}As/SiO_2$ interface. If the traps are located at the $In_{0.53}Ga_{0.47}As$/Si interface, only the cut-off frequency becomes degraded, which again is due to the weaker E-field in the i-region. Similar impacts are also observed for a corresponding plasmonic device, where two extreme cases for the value of the SBH at the metal/i-region interface were examined (0.1 eV and 0.6 eV). The reasons behind these impacts are also similar as in the case of the non-plasmonic device.

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