Performance of Plasmonic Side-Coupled Waveguide Photodetector with Varying Schottky Barrier Height

Qian Ding and Andreas Schenk

Department of Information Technology and Electrical Engineering, ETH Zurich, Gloriastrasse 35, 8092 Zurich, Switzerland
dingq@iis.ee.ethz.ch, schenk@iis.ee.ethz.ch

***Abstract*—The impact of Schottky barrier height (SBH) on the performance of a side-coupled plasmonic waveguide photodetector (WGPD) is theoretically investigated by 3D opto-electrical simulations. A general decrease of the cut-off frequency is observed for all studied barrier heights (0.1 eV to 0.6 eV), most pronounced in the range (0.3 - 0.4) eV. The degradation is an electrostatic effect caused by the formation of the Schottky barrier in the i-region of the device.**

I. Introduction

Several plasmonic photodetectors with bandwidth improvement have been reported recently [1] [2], benefiting from the plasmonic enhancement of the optical field. However, the electrostatic effect of the plasmonic structure on device performance is rarely discussed. Here, we study a side-coupled plasmonic WGPD [3] to demonstrate the impact of the SBH. The non-plasmonic reference device consists of an $In_{0.53}Ga_{0.47}As$ p-i-n diode and a side-coupled Si WG (Fig. 1(a)). The plasmonic counterpart is formed by placing an Ag strip (100/80/40 nm-long/wide/thick along z/x/y-axis) on the i-region (Fig. 1(b)). In both devices, the i-region length along the z-axis is 100 nm, the WG is 240 nm high, and other geometry parameters are set to 200 nm. Details of the modeling method are given in Ref. [4]. We first explore the bandwidth-limiting mechanisms in the non-plasmonic device, proceed with the impact of a varying SBH on the performance of the plasmonic device, and finally discuss its physical origin.

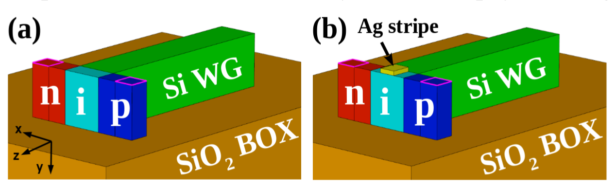

Fig. 1: Sketch of the (a)/(b) non-plasmonic/plasmonic device.

II. Non-Plasmonic side-coupled WGPD

As shown in Fig. 2 (a), the frequency response of the non-plasmonic device exhibits a "double-cut-off" feature, indicated by the change of the curve slope around 300 GHz. The lower (higher) cut-off close to 100 GHz (1 THz) is labeled as "1" ("2"). Using the reference study method [4], the lower cut-off is found to be limited by following processes: drift of holes in the i-region (see green dashed curve in Fig. 2 (a)), both drift and diffusion of electrons in the p-region, and similarly for holes in the n-region (see black and cyan dashed curves in Fig. 2 (a)). The higher cut-off is related to the drift of both types of carriers in the i-region (see blue and green dashed curves in Fig. 2 (a)). The latter observation is simply due to finite transit time of generated carriers in the i-region. For the former case, its dependency on both diffusion and drift of minority carriers is due to the spatial mismatch between E-field and optical generation in the highly doped regions (see Fig. 2 (b)(c)). Consequently, a concentration gradient of minority carriers is formed near the doped/i-region interface (see Fig. 2 (d) for electrons near p/i as example). These carriers must first diffuse into the i-region before they can drift, which slows down the whole collection process. The diffusion mechanism is confirmed by a drop of the quantum efficiency (QE) plateau when strongly suppressing the mobility in these regions (see down-arrow in Fig 2(a)).

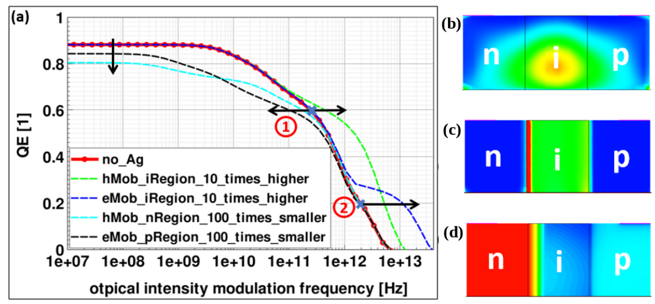

Fig. 2: (a) Frequency response curve of a non-plasmonic device and curves obtained with scaled carrier mobility from reference study. Optical generation rate (b), electric field (c) and electron density (d) profile at -2 V, obtained by a vertical cut in p-i-n direction at distance of 100 nm to the i/Si interface. Color bar from blue to red ranges from 0 to 2×10^{23} $cm^{-3}s^{-1}$ in (b), from 0 to 3×10^{5} V/cm in (c) and from 3×10^{8} to 3×10^{19} cm^{-3} in (d).

III. Plasmonic side-coupled WGPD

A. Impact of varying SBH on Device Response

Simulated response curves of the plasmonic device with different SBHs are presented in Fig. 3 (a), with insertion (b) showing the details where the main effects occur. From Fig. 3 (a) it is clear that a varying SBH does not affect parts of the curve that are related to the original two cut-offs in the non-plasmonic device. The main changes are a new cut-off showing up in the MHz range and a second QE plateau provided the new cut-off frequency is low enough, leading to an overall degradation of the bandwidth. Its dependency on the SBH is

978-1-6654-1276-6/21/$31.00

observed from insertion (b) as follows. For a low SBH (0.1 eV to 0.3 eV), the new cut-off frequency decreases as the barrier becomes higher, while the opposite trend is obtained in case of a high barrier (0.4 eV to 0.6 eV). Thus the performance degradation is most prominent for moderate SBHs (0.3 eV and 0.4 eV), but less severe for very high and low barriers.

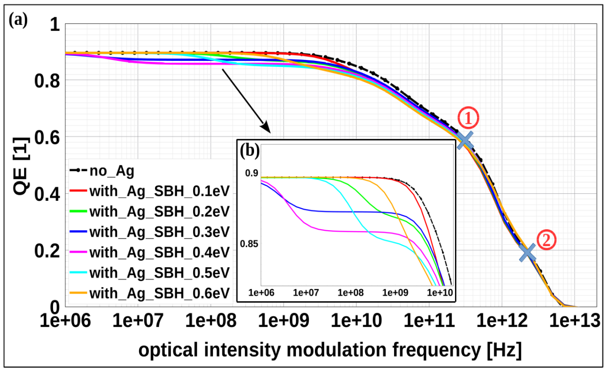

Fig. 3: (a) Comparison of frequency response curves of non-plasmonic and plasmonic devices with SBHs ranging from 0.1 eV to 0.6 eV. A zoomed-in plot is depicted in insertion (b).

B. Electrostatic Origin for Performance Degradation

Above observations indicate that the new cut-off frequency must originate from an additional transport mechanism at the Schottky interface due to placement of the metal. To reveal the physics behind this cut-off, we performed reference studies by scaling down the thermionic emission velocities of both carrier types (by a factor of 100), which are the most relevant for the considered transport besides the SBH. The results are shown in Fig. 4 (a), where SBHs of 0.3 eV and 0.4 eV are chosen as representatives for "low" and "high" barrier. As

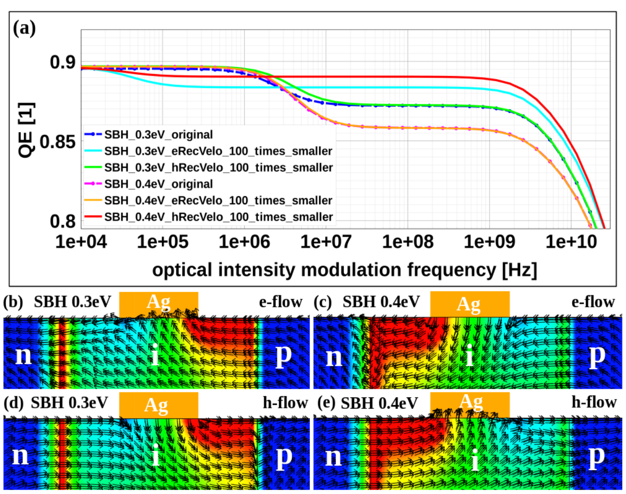

Fig. 4: (a) Frequency response curves of the plasmonic device with a SBH of 0.3 eV and 0.4 eV, together with curves obtained from reference studies using scaled (100 times smaller) thermionic emission velocities of carriers. (b)/(c) Electron and (d)/(e) hole current vector plot in the plasmonic device with a SBH of 0.3/0.4 eV under light at -2 V, obtained by a vertical cut along p-i-n at 100 nm distance to i/Si. Background contour profile represents the corresponding E-field, with color bar from blue to red ranging from 0 to 3×10^5 V/cm.

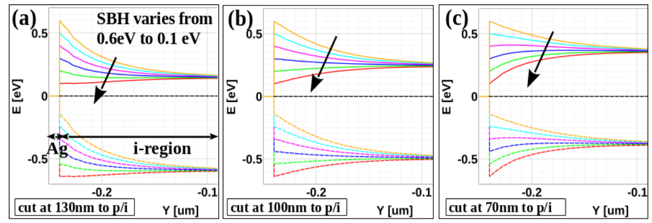

Fig. 5: (a)/(b)/(c) Band diagrams at Schottky interface in plasmonic device with varying SBHs in dark at 0 V, obtained by a vertical cut at 130nm/100nm/70nm far from p/i junction. Colored solid (dashed) and black dashed lines represent CB (VB) edge and Fermi level.

indicated by the red/cyan solid curve, for a high/low barrier the thermionic emission velocity of holes/electrons determines the curve feature related to the new cut-off. This special dependency on carrier type can be understood from the current vector plot in Fig. 4 (b) to (e). The new cut-off is due to the carriers that flow towards the metal and then tend to reverse their direction. This is the e/h-flow for the low/high SBH of 0.3 eV/0.4 eV, as shown in Fig. 4 (b)/(e).

This described behavior is related to the change of band bending in the i-region upon formation of the Schottky interface, where the bending direction flips in the case of moderate SBHs. To illustrate this idea, band diagrams at the Ag/i interface cut at three positions (130nm/100nm/70nm from p/i interface) are shown in Fig. 5 (a) to (c) for all SBHs. First, for large SBHs (0.6 eV to 0.4 eV), the band bends strongly upwards far from the p/i junction but less when getting closer to it (see orange, cyan and magenta curves trend from Fig. 5 (a) towards (c)). Specifically in the lowest case (0.4 eV), the direction of band bending is flipped. Thus, the E-field first points towards the metal near the n/i junction, and then tends to change its direction moving towards the p-side, which explains the observation in Fig. 4 (e). Furthermore, the loss of these carriers flowing towards the metal has the side effect of a second lower QE plateau seen in Fig. 3 (b). For small SBHs the logic is the same, but the situation is the opposite. Here the highest barrier of 0.3 eV causes a band bending flip and the corresponding current flow depicted in Fig. 4 (b). The change of the band bending with varying distance to the p-side is because the presence of the p/i junction affects the band alignment at the Schottky interface, as explained in Ref. [4].

CONCLUSION

A new lowest cut-off frequency is found in a plasmonic WGPD with varying SBH. This kind of degradation is most severe for SBHs of 0.3 eV and 0.4 eV. It is caused by the current flow towards the metal due to the modified band bending near the Schottky interface.

REFERENCES

[1] Y. Salamin *et. al*, "100GHz Plasmonic Photodetector", ACS Photonics vol. 5 (8), 2018.
[2] J. Gosciniak *et. al*, "High-bandwidth and high-responsivity waveguide-integrated plasmonic germanium photodetector," J. Opt. Soc. Am. 2019.
[3] Q. Ding *et. al*, "Design strategy for monolithically integrated photodetector and improvement using plasmonics", Conference NUSOD, 2019.
[4] Q. Ding *et. al*, "Electrostatic impacts of plasmonic structure on the performance of monolithically integrated hybrid III-V/Si waveguide-coupled photodetectors", OSA Continuum 2021.