Scaling Effects on the Plasmonic Enhancement of Butt-Coupled Waveguide Photodetectors

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***Abstract*—We employed 3D opto-electrical simulations to study the scaling effects of a plasmonic structure on the optical performance of butt-coupled waveguide photodetectors by placing an Ag stripe on top of the intrinsic region. It is found that cut-offs which are limited by carrier drift in the high-field region of the non-plasmonic device improve with longer and wider stripe, while the metal thickness has only little impact. Furthermore, the diffusion and low-field drift limited cut-offs can be eliminated with metal stripes longer than 400 nm.**

I. Introduction

Monolithically integrated photodetectors (PDs) with ultra-fast and broadband detection are required for optical links in data centers. Their detection speed can be improved by structure miniaturization to reduce the carrier transit time. However, further down-scaling of conventional PDs is restricted by the diffraction limit. Plasmonic devices become attractive due to their ability to overcome this bottleneck, and different types of plasmonic PDs have been recently reported [1] [2]. In this work, we first study the physical mechanisms limiting the response of a previously designed non-plasmonic butt-coupled waveguide photodetector (WGPD) [3], and then explore their impacts on the optical performance when scaling the plasmonic structure. All investigations are conducted using coupled 3D opto-electrical simulations with *Sentaurus Electromagnetic Wave (EMW) Solver* [4] for FDTD calculation and *Sentaurus Device* [4] for electrical transport. The Ag/intrinsic region (i-region) interface is assumed as ideal Schottky type (barrier height 0.6 eV) without image-force lowering.

II. Device Structure

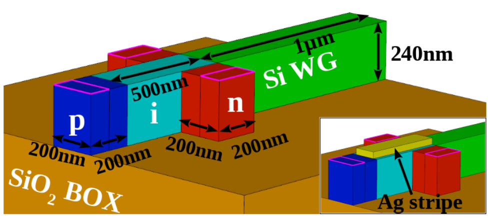

Fig. 1: Sketch of non-plasmonic and plasmonic (inserted) butt-coupled waveguide photodetectors.

The studied non-plasmonic device consists of an $In_{0.53}Ga_{0.47}As$ p-i-n diode and a co-planarly coupled Si waveguide (WG) (Fig. 1), with i-region length (500 nm) and WG height (240 nm) optimized for performance [3] (other dimensions fixed by fabrication). The plasmonic device is formed by placing an Ag stripe on top of the i-region.

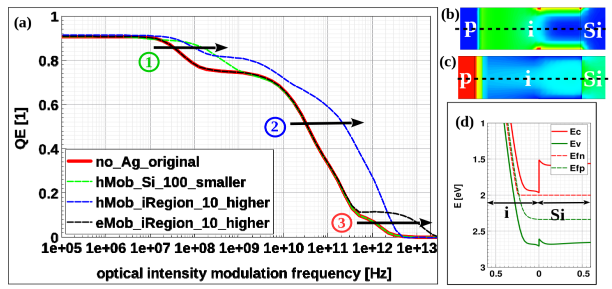

Fig. 2: (a) Frequency response of non-plasmonic device with scaled carrier mobility. (b) E-field. (c) Hole density at -2 V obtained by horizontal cut at 120 nm below top surface. Color bar from blue to red ranges from 0 to 2e5 V/cm in (b) and from 3e10 to 3e19 cm^{-3} in (c). (d) Band diagram cut along black dashed line in (b)(c).

III. Frequency Response of Non-Plasmonic Device

The frequency response of the non-plasmonic device (red solid curve in Fig. 2 (a)) reveals three cut-offs, with the lowest/middle/highest near 30 MHz/40 GHz/1 THz (labeled as 1/2/3 in Fig. 2(a)). Understanding the origins of these limits is essential for the subsequent study of the plasmonic device. We apply the reference study method, where the response curve is simulated with a modified carrier mobility in certain regions. The limiting mechanisms are found by comparison with the original curve, as its shape only changes if the considered transport process is relevant. Furthermore, when a cut-off vanishes with strongly reduced mobility in a low-field region, it is diffusion-limited. When the cut-off frequency simply decreases by roughly the same factor as the mobility (or vice versa), it must be related to drift, because the drift velocity scales with the mobility. With this method it is found that the middle (highest) cut-off is caused by drift of holes (electrons) in the high-field i-region as expected (blue and black dashed curves in Fig. 2(a)). The lowest cut-off originates from hole drift in the low-field i-region near the WG (Fig. 2. (b)) and hole diffusion from Si (green dashed curve in Fig. 2 (a)). The hole density gradient near the WG (Fig. 2 (c)) is caused by the lack of a drift field and the small potential well related to the valence band offset at the i/Si interface (Fig. 1 (d)).

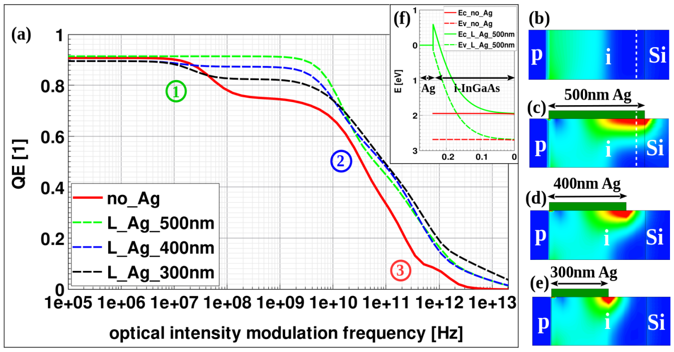

Fig. 3: (a) Frequency response of non-plasmonic and plasmonic device with scaled length. E-field in device with (b) no (c) 500 nm (d) 400 nm (e) 300 nm long Ag at -2 V, obtained by central vertical cut along p-i-Si direction. Color bar from blue to red ranges from 0 to 3e5 V/cm. (f) Band diagram cut along white dashed line in (b)(c).

IV. Effects of Scaling the Plasmonic Structure

All three dimensions of the metal stripe are studied in this work, i.e. its length in light-propagation direction, its width along the n-i-n collection direction, and its thickness. The impacts of scaling can be deduced from comparison with the non-plasmonic device.

A. Length of Metal Stripe

500 nm/400 nm/300 nm long stripes are studied, with length measured from p/i junction towards WG. Compared with the non-plasmonic device, the lowest cut-off disappears for 500 nm long Ag, while the two higher cut-off frequencies increase without a unique scaling tendency (Fig. 3 (a)). These effects are related to the growing electric field in the i-region induced by the metal (Fig. 3 (b) to (e)) as result of the Schottky barrier (SB) formation (Fig. 3 (f)). As the stripe gets shorter, the field near the i-region/WG interface becomes weak again, and thus the lowest cut-off reappears. The metal slightly increases the field in the high-field i-region, which increases the two higher cut-off frequencies. However, since this field enhancement is determined by the SB height, it does not scale with the stripe length.

B. Width of Metal Stripe

The width of the stripe is varied from 180 nm to 60 nm in steps of 40 nm, with length and thickness kept as 500 nm and 40 nm, respectively. As shown in Fig. 4 (a), two cut-off frequencies limited by drift in the high-field i-region of the non-plasmonic device increase with wider stripe, the minimum width for improvement being 60 nm. This is due to the metal-induced field enhancement in the i-region as explained above. However, this enhancement becomes weaker as the stripe becomes narrower (Fig. 4 (b) to (d)), thus the improvement scales down with stripe width.

C. Thickness of Metal Stripe

The stripe thickness is scaled from 20 nm to 100 nm in steps of 40 nm, while the length and width are fixed to 500 nm and 140 nm, respectively. As seen in Fig. 5 (a), scaling the thickness hardly influences the cut-off frequencies because of the unchanged electric field in the i-region (Fig.5 (b) and (c)). The latter depends is on the SB height as mentioned before. Fig. 5 (a) reveals that the QE slightly drops in the case of 20 nm-thick Ag. This is due to lower plasmonic-enhanced optical generation when the metal thickness comes under 20 nm (Fig. 5 (d) and (e)).

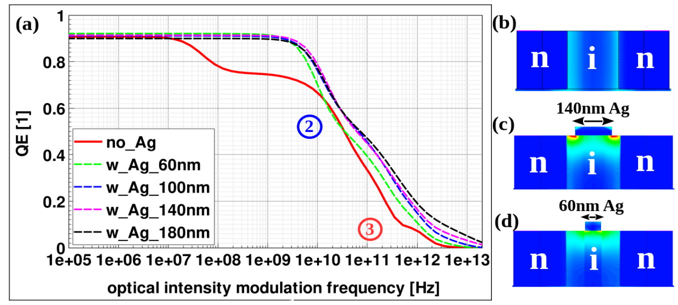

Fig. 4: (a) Frequency response of non-plasmonic and plasmonic device with scaled width. E-field at -2 V in non-plasmonic (b) and plasmonic device with (c) 140 nm (d) 60 nm wide stripe, obtained by vertical cut in n-i-n direction at 100 nm distance to WG. Color bar from blue to red ranges from 0 to 2e5 V/cm.

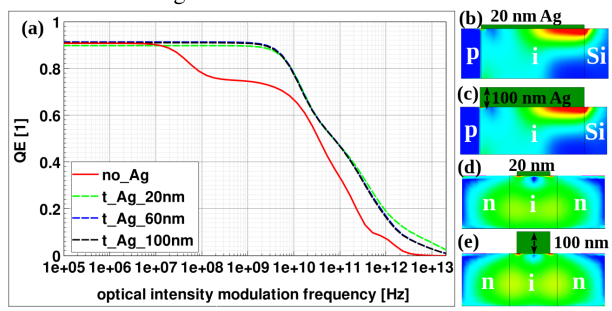

Fig. 5: (a) Frequency response of non-plasmonic and plasmonic device with scaled thickness. (b)/(c) E-field at -2 V in device with 20 nm/100 nm thick Ag, obtained by a central vertical cut in p-i-WG direction. (d)/(e) Optical generation rate in device with 20/100 nm thick Ag, obtained by a vertical cut in n-i-n direction at 100 nm distance to WG. Color bar from blue to red changes from 0 to 3e5 V/cm in (b)(c) and from 1e22 to 1e24 $cm^{-3}s^{-1}$ in (d)(e).

Conclusion

We showed that longer and wider metal stripes in a plasmonic butt-coupled WGPD improve the cut-off frequencies which are limited by carrier drift in the high-field i-region. The reason is given by the metal-induced field enhancement due to SB formation. Scaling the thickness hardly affects the performance. Length scaling also impacts diffusion and low-field drift, the mechanisms responsible for the lower cut-offs in the non-plasmonic device.

References

[1] Y. Salamin *et. al*, “100GHz Plasmonic Photodetector”, ACS Photonics vol. 5 (8), pp. 3291-3297, 2018.
[2] J. Gosciniak *et. al*, ”High-bandwidth and high-responsivity waveguide-integrated plasmonic germanium photodetector,” J. Opt. Soc. Am. B 36, pp. 2481-2491, 2019
[3] Q. Ding *et. al*, ”Design strategy for monolithically integrated photodetector and improvement using plasmonics”, Conference NUSOD, 2019.
[4] Sentaurus Device & EMW Solver, Version O-2018.06.
[5] L. Novotny, ”Principle of Nano-Optics”, Cambridge Uni. Press, 2006.
[6] P. B. Johnson *et. al*, Optical Constants of the Noble Metals, Phys. Rev. B 6, pp. 4370, 1972.
[7] S. Adachi. Optical dispersion relations for GaP, GaAs, GaSb, InP, InAs, InSb, $Al_xGa_{1-x}As$, and $In_{1-x}Ga_xAs_yP_{1-y}$, J. Appl. Phys. 66, pp. 6030-6040, 1989.