Metasurface Colloidal Quantum Dot Photodetectors

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Metasurface Colloidal Quantum Dot Photodetectors

Photodetectors and photodiodes are used to achieve the desired results, taking advantage of metasurfaces, that influence parameters such as quantum efficiency, responsivity, gain.

On of the key points of these devices is the low voltages needed, making them compatible with CMOS technology.

Metasurface:

Scientists are creating new materials or nanostructured materials that exhibit unusual electronic and optical properties.

Colloidal:

Mixture in which two distinct entities can be recognized, one of which is the dispersant material while the other consists of insoluble particles characterized by nano-micro-metric dimensions.[1]

Quantum Dot:

Small NPs (2-10 nm) made of a semiconductor material which have electronic and optical properties different from the same material in the form of bulk.

Photodetectors:

Devices that measure incident optical power and convert it into a measurable quantity.

Design and fabrication

- The proposed stucture for the photodetector and photodiode is an example of metal-insulator-metal (MIM) metasurface perfect absorber.
- Polarization sensitive devices can be obtained by introducing features for x-polarized and/or y-polarized light.
- This allows polarization-sensitive or polarization-insensitive absorption.

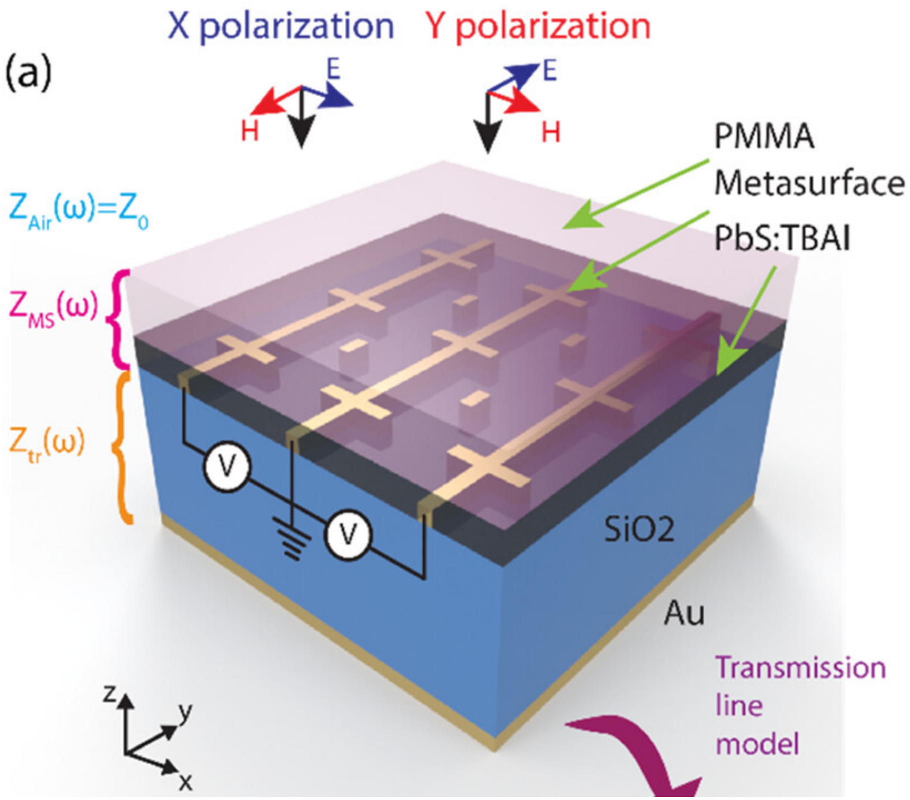

Figure 1. Schematic representation metasurface-enhanced photodetector

Design and fabrication

Using aluminum instead of gold on every other bar electrode in the metasurface, a Schottky-type photodiode is obtained

The metallic structure has two purposes:

Increasing absorption

Extracting photogenerated charges

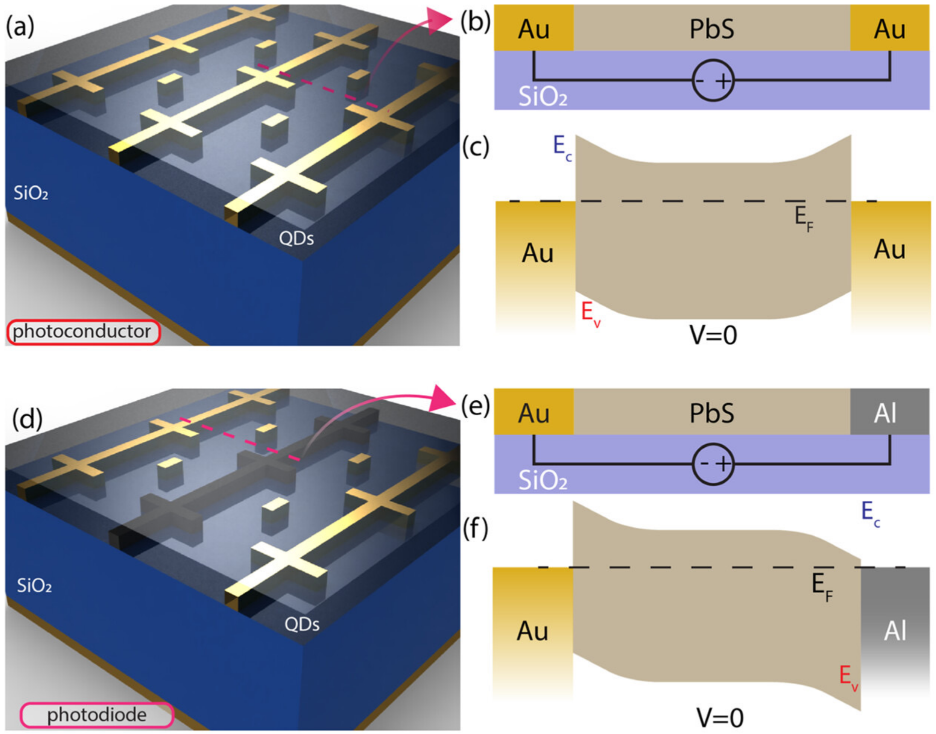

Figure 2. Device physics of metasurface photodetectors. Structure and relative band structure.

Design optimization

PbS Quantum Dots with an excitonic peak absorption near 1550nm

Optimization of the design are made to maximize absorption and minimize reflection at wavelengths close to the excitonic peak.

To obtain low reflection, an equivalent circuit of the detector is proposed.

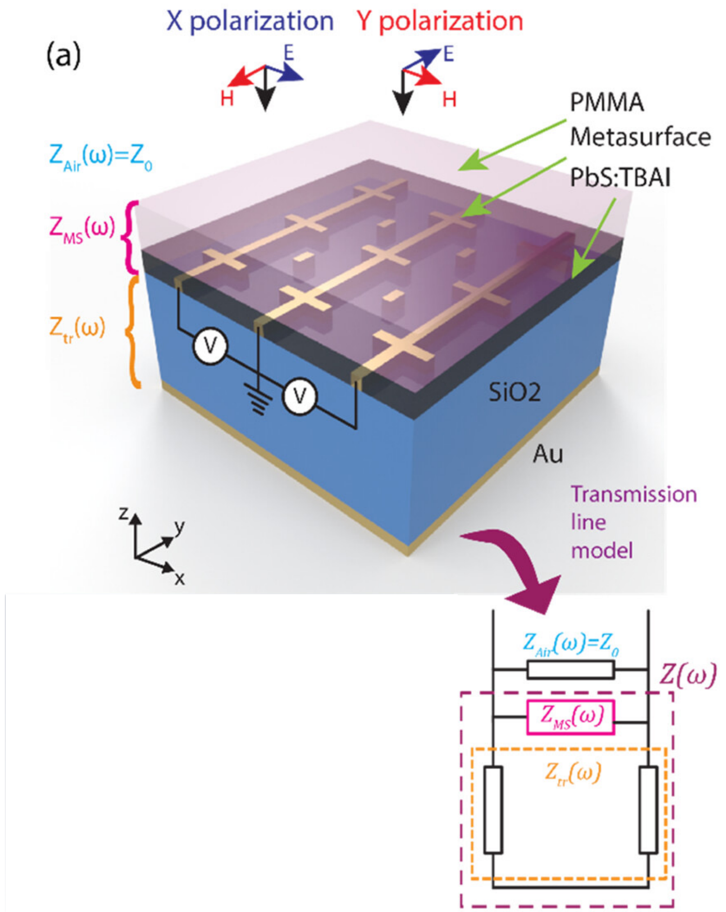

Figure 3. Equivalent circuit of the layers.

Design optimization

The metasurface consists of an impedance

$$Z_{MS}(\omega)$$

and a transmission line with impedance

$$Z_{tr}(\omega)$$

The detector features an impedance

$$Z^{-1} = Z_{MS}^{-1} + Z_{tr}^{-1}$$

GOAL : minimize the reflection between air with free space impedance and the metasurface detector

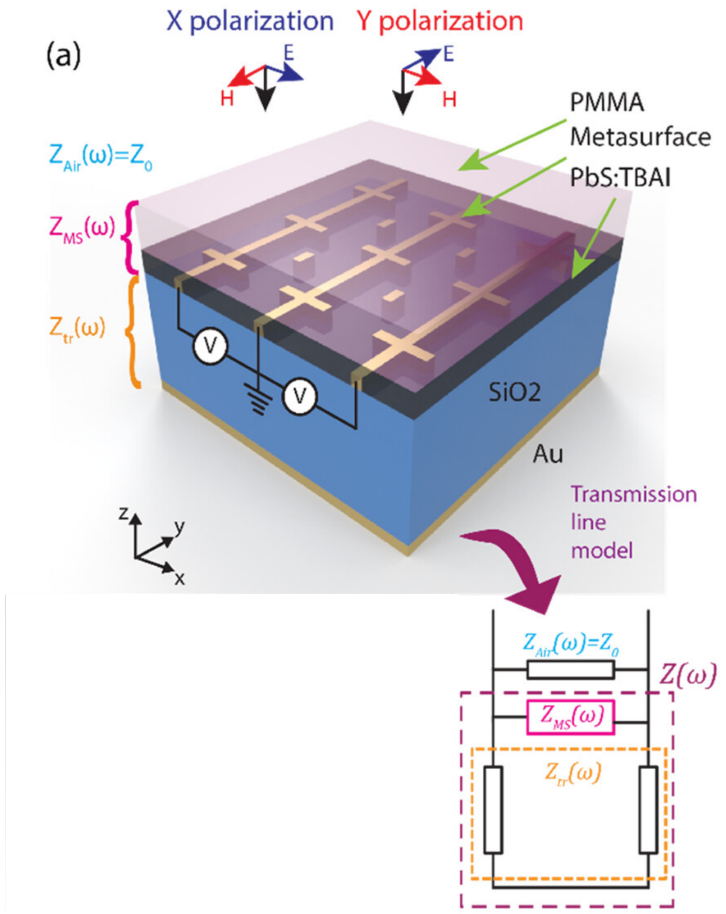

Figure 3. Equivalent circuit of the layers.

Design optimization

Reflection at the interface, using Fresnel equations:

$$R(\omega) = \left|\frac{Z_0 - Z(\omega)}{Z_0 + Z(\omega)}\right|^2$$

The previous equation is minimized when the following conditions are met:

$$Re(Z(\omega)) = Z_0$$

$$Im(Z(\omega)) = 0 \Rightarrow Im\left(\frac{1}{Z_{tr}(\omega)}\right) = -Im\left(\frac{1}{Z_{MS}(\omega)}\right)$$

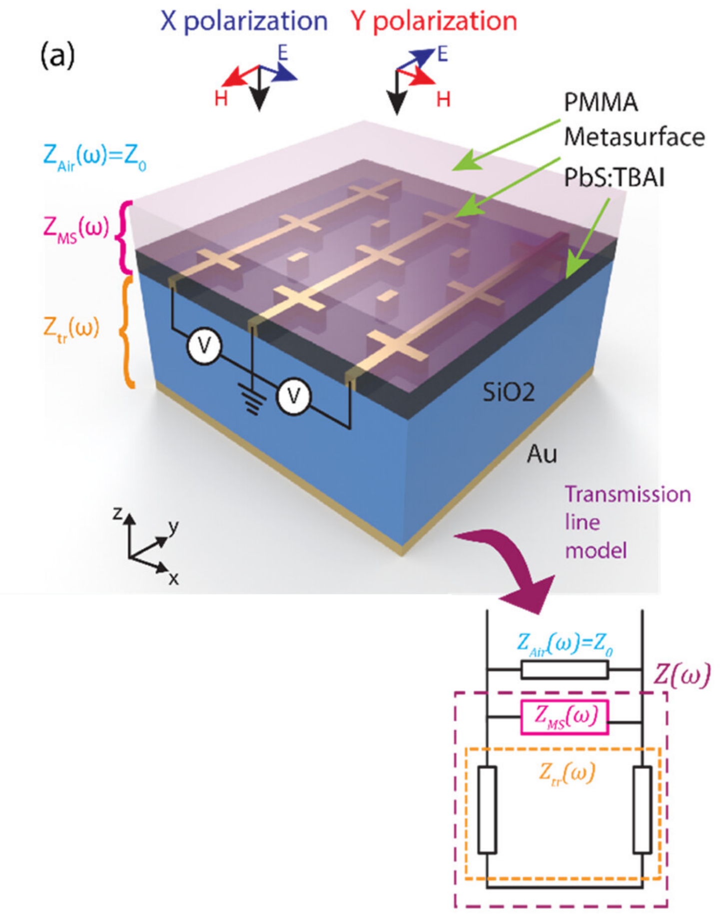

Figure 3. Equivalent circuit of the layers.

Main results – Responsivity

The responsivity

$$R_{th} = \frac{I_{light} - I_{dark}}{P_{in}}$$

is shown for different bias and illumination powers with a laser at 1530 nm for powers between 18pW and 14 nW.

Responsivity values of $8.2\times10^{3}\ A/W$ are measured for an on-chip power of $20.5\ pW$ and a bias voltage of $5\ V$.

These are among the highest reported values for QD devices using voltages below $10\ V$.

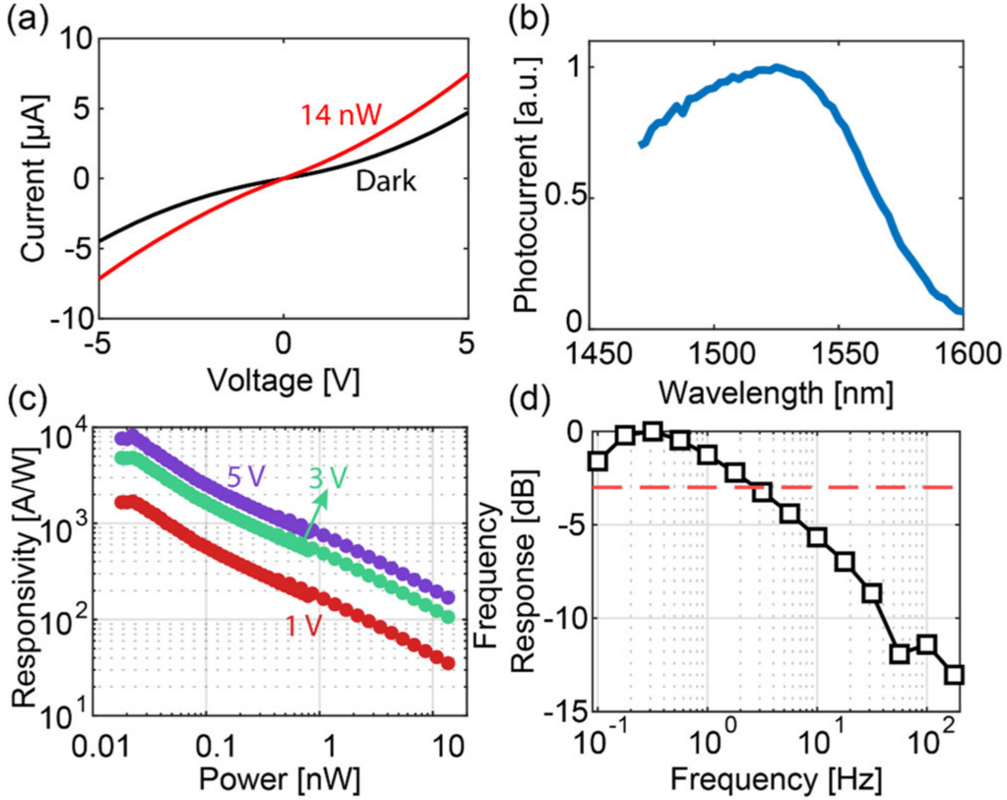

Figure 5. Optoelectronic characterization of a photoconductor optimized for x-polarized light.

Main results – Responsivity

We find ~75% lower dark currents and lower responsivities in the y- device.

The frequency response of the y- device is nearly the same as the one of the x- device.
This means that the frequency response is dominated by the lifetime of the electron minority carriers (ms to s) and not by the drift time of hole majority carriers (us).

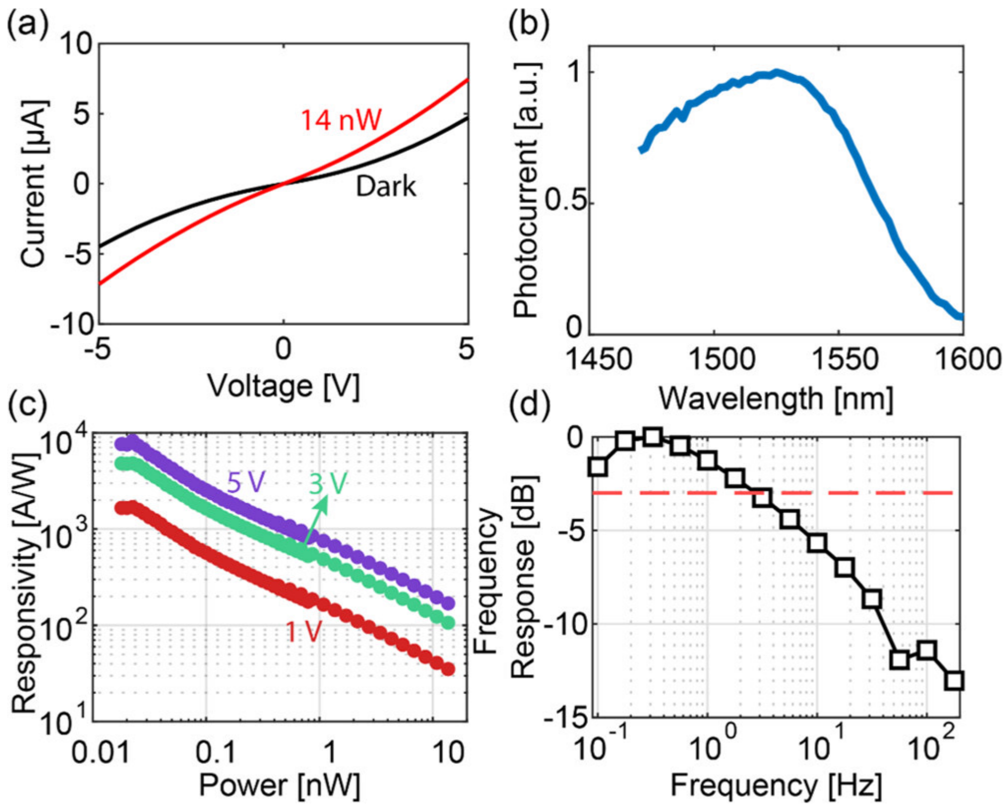

Figure 5. Optoelectronic characterization of a photoconductor optimized for x-polarized light.

Main results – Bandwidth

Using the measured bandwidth and estimating a gain of

$$G_{1V} \approx 0{,}64 \times 10^5 \ \text{@1V}$$

we report a gain-bandwidth product of $1{,}92 \times 10^5\, Hz$

The QD photoconductors feature high gain but limited bandwidth.

By using aluminum and gold as contacts, we can form a barrier for holed in PbS thin films and plasmonic losses are within the same range as those of gold.

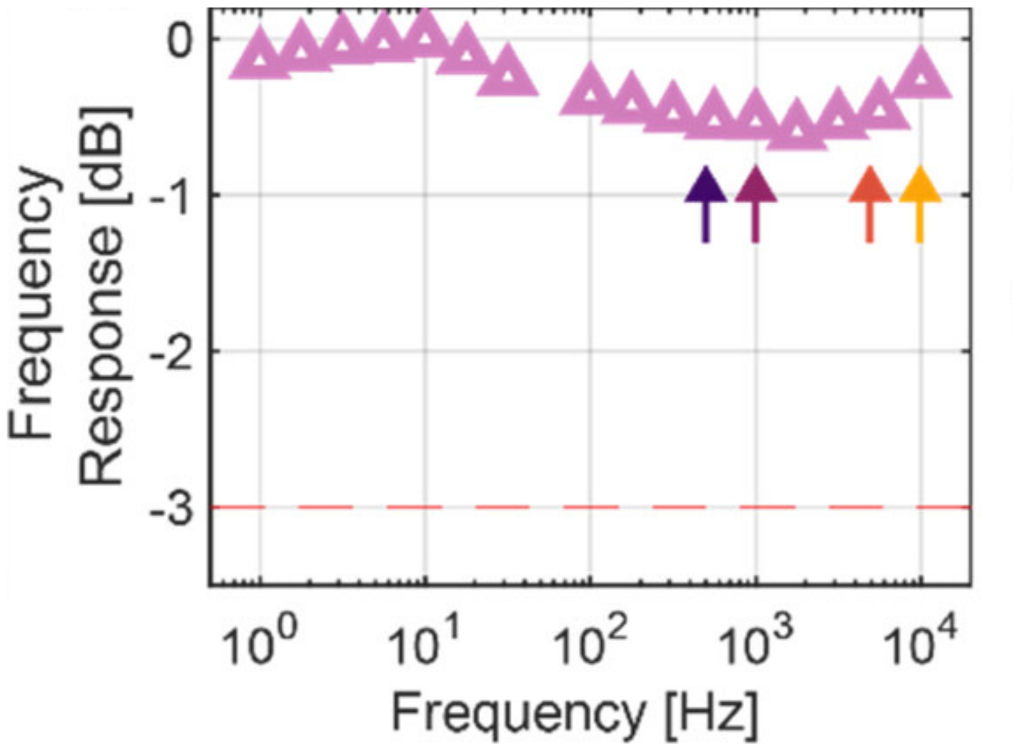

Figure 6. Frequency response measured at the peak wavelength.

Conclusions

By matching the optical impedance to the free space impedance, the metamaterial exhibit overall near-unity absorption, which leads to a 10-fold improvement of the absorption of light in the QD layer having the same thickness

It's possible to achieve high sensitivities, while requiring only thin QD layers. If all lithography steps are done prior to depositing quantum dots, we can pattern the QD layer only where it's needed, minimizing the fraction of toxic material in our devices.

Conclusions

The versatility of the design introduces charge-selective contacts by replacing every other gold contact with aluminum. This way, Schottky-type photodiodes are formed, offering several orders of magnitude higher frequency response.

Thanks to the modularity of the design and by tuning the metamaterial design parameters, sensing in different spectral regions can be achieved.

Adds-on (Schottky photodiode)

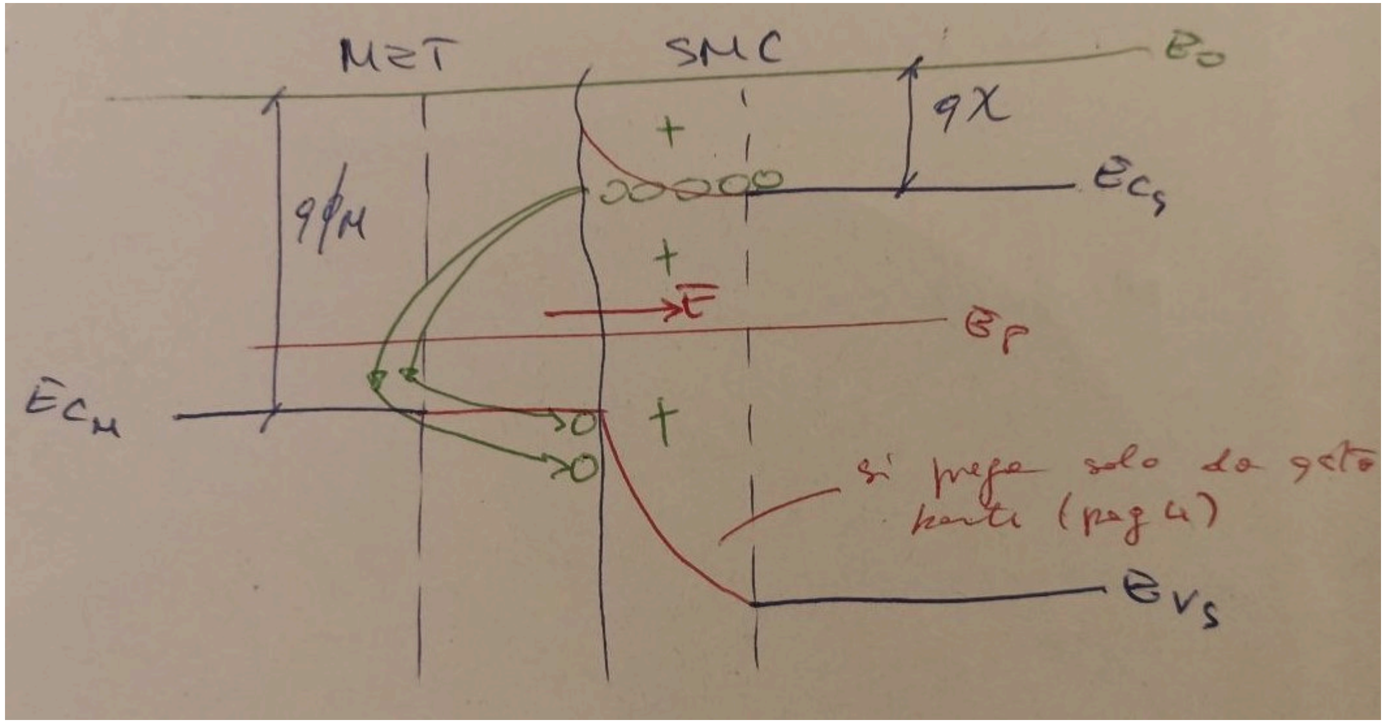

Figure 7. Band diagram of the metal-semiconductor junction

Let's consider a metal-semiconductor junction (heterojunction).
We have electroncs in the conduction band of the semiconductor that are at higher energy than those of the metal in the conduction band.
To establish an equilibrium situation, electrons tend to move down, but are repelled toward the interface.

Adds-on (Schottky photodiode)

Given the relation between energy bands and potential, we obtain a bending of the bands, caused by the effect of the ionic charges.

We exploit the ASCE (Abrupt Space Charge Edge) hypothesis, instead of solving the 3D Poisson equation for the potential. From the charge distribution we obtain the electric field and the potential of out system.

In the case of Schottky photodiodes, we have a reduced potential barrier, thus having lower activation threshold and as a result we have the fast response.

This can be the reason of higher orders of frequency response and responsivity.

Sitography and biography

[1] https://goldbook.iupac.org