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Optical-Electronic Simulation of a GaAs Metal-Semiconductor-Metal (MSM) Photodetectors

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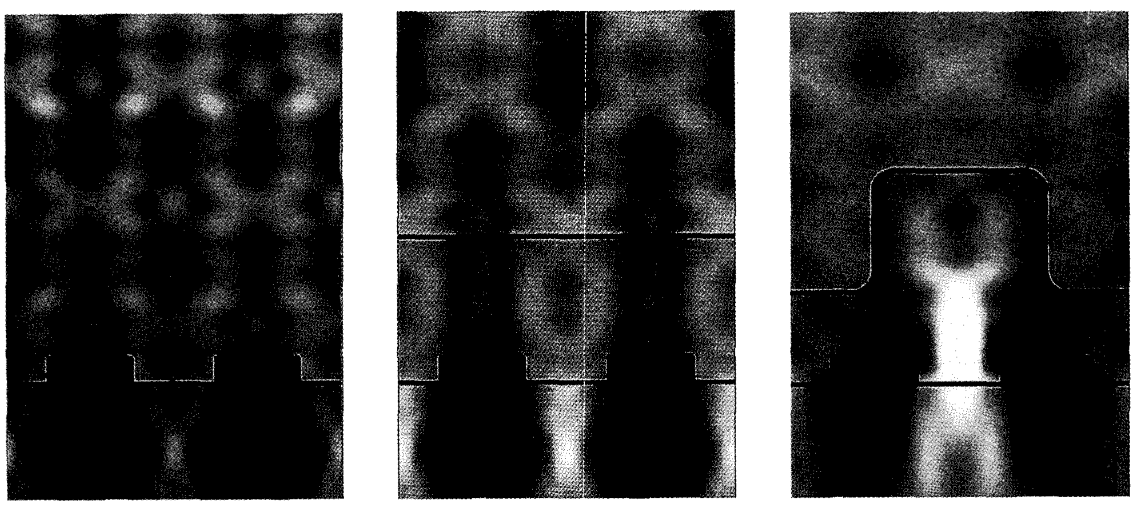
A complete optical-electronical simulation of a GaAs based MSM photodetector [1, 2] is presented. In the modeling, rigorous electromagnetic methods for the light propagation have been combined with particle-based Monte-Carlo electronic device simulation methods.

The performance of light sensitive semiconductor elements such as photodetectors, photodiodes, CCD cells or solar cells depends on the flux and distribution of light intensity within the structure under examination as well as on material and electronic parameters such as band structure and doping profiles. Depending on the application, performance may refer to sensitivity, short response times, wavelength selectivity or other characteristics.

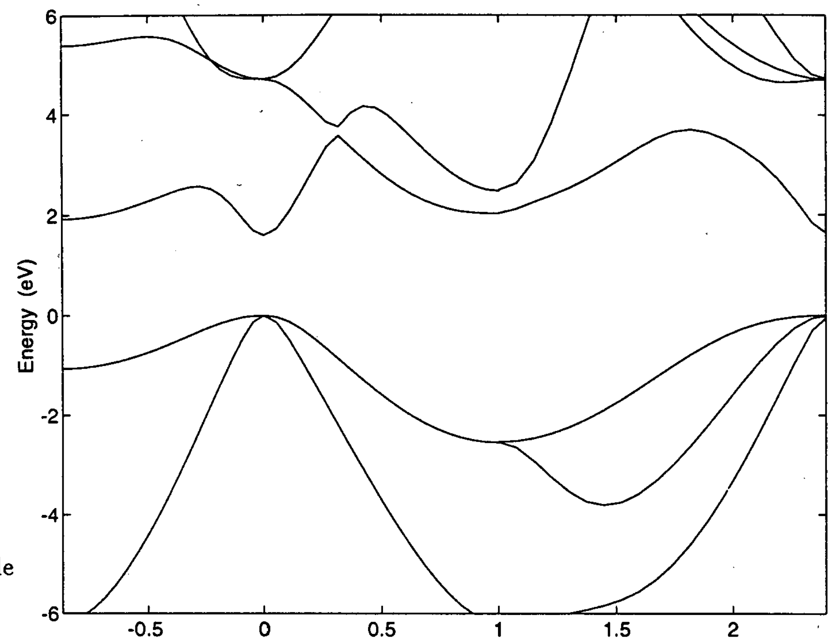
One possibility to improve and optimize performance of a detector element is to influence the light intensity distribution within, which in turn depends on the geometric and optical parameters of the structure as well as on the properties of the incident radiation (wavelength, polarization, angle of incidence etc.). For structures which are large compared to the wavelength, sufficiently good approximations can be obtained by means of simple geometrical optics models. As feature sizes become smaller, the errors caused by neglecting diffraction and interference effects increase. When the feature sizes are below the order of a few wavelengths, rigorous electromagnetic models are necessary to obtain reasonably accurate results. In this investigation, rigorous electromagnetic theory and Monte Carlo simulation have been joined to study the complex optoelectronic behavior of this device.



GMT computation of intensity distributions for different MSM detector designs: basic structure (left), with antireflection layer (middle) and with incoupling grating (right). S-polarized, monochromatic plane wave ($\lambda = 620\,\mathrm{nm}$) perpendicularly incident from above.

The Generalized Multipole Technique (GMT) [3] was used for the rigorous simulation of the light propagation. GMT is a full-wave, frequency-domain electromagnetic method that can solve the wave equation in a model consisting of piecewise homogeneous and linear domains. The electromagnetic simulation yields a light intensity distribution in the semiconductor structure.

As light impinges on the detector structure, electrons are excited into conduction bands according to very complex distributions, depending critically on the spectrum of the incident light and the electronic band structure. Terminal response is then governed to a large degree by excitation and position- and energy-dependent picosecond-scale relaxation of high-energy carriers. For this reason it is imperative to simulate the electronic transport for such optoelectronic devices with a realistic physical model capable of describing arbitrary non-equilibrium distributions and the complicated carrier transport and relaxation dynamics. The particle based Monte Carlo technique is ideal for this purpose, and the simulator of reference [4] modified to include carrier-carrier scattering has been used throughout this investigation. Time-dependent terminal currents are evaluated with the domain integration technique of reference [5].



Electronic band structure of GaAs.

With this combination, we examine the response time and efficiency of different designs for an GaAs-based, interdigitated MSM detector. The detector is approximated as a 2D, periodic structure. The metal fingers are assumed to be perfectly conducting, and have width and spacing of 0.41 μm. Various optical designs aimed at improving efficiency, such as antireflection coatings, micro-lens structures and incoupling gratings, are studied. The behavior under different illumination parameters (wavelength, polarization, angle of incidence) is investigated.

[1] Yi Chen et al. 375-GHz-bandwidth photoconductive detector. *Applied Physics Letters*, 59(16):1984–1986, October 1991.

[2] J. J. Kuta et al. Coupled-wave analysis of lamellar metal transmission gratings for the visible and the infrared. *Journal of the Optical Society of America A*, 12(5):1118–1127, May 1995.

[3] Ch. Hafner. *The Generalized Multipole Technique for Computational Electromagnetics.* Artech House Books, 1990.

[4] P. D. Yoder and K. Hess. Application of a new multi-scale approach to transport in a GaAs/AlAs heterojunction structure. In N. Balkon, editor, *Negative Differential Resistance and Instabilities in 2-D Semiconductors*, pages 99–108. Plenum, New York, 1993.

[5] P. D. Yoder, K. Gärtner, and W. Fichtner. A generalized Ramo-Shockley theorem for classical to quantum transport at arbitrary frequencies. *Journal of Applied Physics*, 79:1951–1954, 1996.