Numerical Modeling of Nanoscale Silicon Photodetectors that Use Electromagnetic Resonance Modes to Enhance Performance

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ABSTRACT

Several high responsivity, high bandwidth, low bit error ratio (BER) nanoscale Silicon (Si) photodetectors are modeled including bulk Si metal-semiconductor-metal photodetectors (MSM-PD), MSM-PDs fabricated on silicon-on-insulator substrates, and avalanche photodiodes. The authors have analyzed surface plasmons and other electromagnetic resonance modes (ER) and optical modes (OM) including Wood-Rayleigh anomalies and diffraction in structures with nanometer-sized features and have found that the use of combinations of these modes can perform light channeling and light localization that can be applied to enhance the performance of the photodetectors. In this work, the ERs and OMs within the nanoscale Si photodetecting structures are modeled, all aspects of electron and hole generation, recombination, drift and multiplication are calculated, eye diagrams are constructed, and the maximum bandwidth, responsivity, quality factor and BER are calculated given a 256 bit non-return to zero pseudo-random bit sequence optical signal.

Keywords: Silicon, photodetectors, surface plasmons, gratings, cavity modes, optical communications

1 INTRODUCTION

Photodetectors in the visible spectral range ($\lambda = 400 \rightarrow 700nm$) and short wavelength IR ($\lambda = 700nm \rightarrow 2\mu m$) have been used for innumerable applications over the last twenty years. Silicon (Si) based photodetector applications include: very short range (VSR) fiber-based 850nm communication systems, 850nm wireless communication systems, imaging systems in the visible spectral range and single photon counting detectors [1]. These Si-based photodetectors however, being fabricated on an indirect bandgap material with a low absorption constant (i.e., Si), all have the same problem of relatively poor performance in terms of bandwidth *and* responsivity compared to photodetectors fabricated on direct bandgap materials [1]. To solve this problem, a tremendous amount of research has been performed but it usually involves complex fabrication techniques and usually resulting in only moderate enhancement in performance [2,3]. One area of research however, has not received nearly the same amount of attention in vertically illuminated photodetector devices is how light gets into the photo-detecting material in the first place and how it is subsequently distributed throughout the active area of the device. Almost invariably, device engineers model these devices with two incorrect assumptions: 1) the portion of the incident beam that falls on the metal contact is always reflected and automatically leads to a large loss in sensitivity. 2) the portion of the incident signal that falls between the metal contacts travels straight down in the Si and the intensity decays exponentially as the optical signal is converted into electron-hole pairs [4]. With device fabrication technology currently being able to achieve feature sizes on the order of 130nm, these two assumptions can be drastically incorrect and a variety of electromagnetic resonance (ER) modes and optical modes (OM) can occur, which can be exploited to produce dramatically improved device performance. These ERs and OMs include surface plasmons, Fabry-Perot cavity modes and diffraction modes used *in combination* to produce the ideal electromagnetic field intensity profile for a particular application. In this paper, we theoretically demonstrate enhanced performance of three nanoscale Si based devices by tapping into various ER modes.

2 OPTICAL MODELING AND ELECTROMAGNETIC RESONANCE MODES

In this paper, we study three Si based photodetectors in the nano scale: 1) Bulk Si metal-semiconductor-metal photodetector (MSM-PD) 2) MSM-PDs fabricated on SOI substrates 3) Si based Avalanche photodiode. All the above-mentioned devices modeled in this paper, have one thing common in geometry, and they are all similar to a periodic optical transmission grating with slits. Recently, there has been an increasing interest in these subwavelength/nano optical transmission gratings because of the their ability to produce extraordinary transmission by tapping into the various ERs and OMs that occur in these gratings [5-7]. To briefly summarize there are five types of ERs and OMs that occur in the proposed devices that can be used in combination to significantly enhance the performance of these devices:

1) Horizontally Oriented Surface Plasmons (HSP): Coupled charge oscillations (and their associated electromagnetic fields) that are oriented along **horizontal** metal/dielectric interfaces within the photodetector.

2) Vertical Cavity Modes (VCM): Fabry-Perot like resonances inside the slits between the metal contacts.

3) Wood-Rayleigh Anomalies (WR): The onset of a diffracted mode. This mode produces a propagating wave that is at grazing incidence to the structure.
4) Diffracted Modes (DM): Of course, these are the well known diffracted modes in periodically patterned structures. However, these modes will be used in combination with VCM and Fabry Perot modes to significantly enhance device performance.
5) Fabry-Perot Resonant Modes (FPM): These are resonant modes established between the metal contact and the oxide layer in a SOI based detector.

The reader is referred to ref. [5-7] for a detailed discussion on the properties of these ER modes and their structural and material dependence. The optical modeling of all of these devices is performed using the extended surface impedance boundary condition (ExSIBC)[7]. Each of the mentioned devices requires a different combination of these ER modes to produce the ideal field required for enhancing the performance of the devices as will be discussed below.

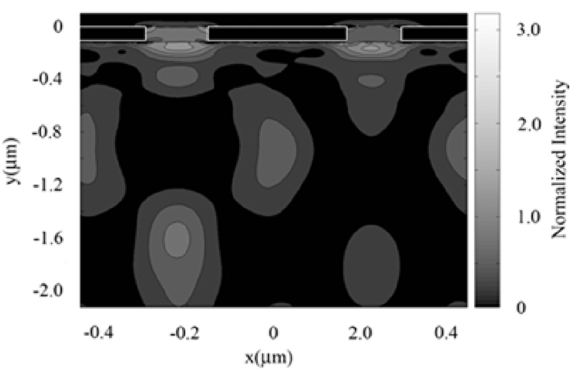

Fig.1 Bulk Si MSM-PD

2.1 Bulk Si MSM PD

In a Bulk Si MSM-PD, minimizing the 0^{th} order reflectance (R_o) is desired in order to maximize the amount of the optical signal that remains in or near the MSM structure. However, one also wants to minimize 0^{th} order transmitted beam (T_o) because this radiating field component propagates deep into the Si thereby reducing device speed. Techniques to simultaneously minimize R_o and T_o using HSPs, WRs and CMs, and hybrid modes (i.e., modes consisting of combinations of these HSPs, WRs, and CMs) in lamellar gratings are explained in detail in [7]. In [7], it was found that a desirable electromagnetic field profile for a Si MSM-PDs was obtained when a WR/diffracted mode is aligned with a CM mode producing a hybrid-like ER/optical mode. This WR/DM/VCM hybrid mode is much different than the HSPs that past researchers have tried to use to enhance Si MSM-PD device performance. In fact, we have found that HSPs need to be eliminated because they *inhibit* transmission and produce large absorption leading to dramatically reduced device performance. It was also found that the most effective way to align the WR and CM was to start with a structure where the CM mode had a slightly larger energy than the HSP/WR pair and then to increase the dielectric constant of the material in every other groove. This method not only allowed the alignment of the minima of R_o and T_o but also inhibits the HSP component of the HSP/WR pair, which are undesirable as mentioned earlier. Fig.1 shows the electromagnetic energy density produced by the 850nm, normal incident beam. The structure is composed of Au contacts with a pitch of d = 900nm, slit opening c = 150nm, height of the metal contacts h =125nm, and every other groove is composed of dielectric with ε=2. As can be seen from the Fig.1, there is a large concentration of light within the top 0.5μm of the Si, this is a result of the light localization produced by the WR mode. Also, looking at the Poynting vector [7](not shown here due to space constraints), it has been found that light falling on the top metal contacts is channeled into the substrate by the use of these ER modes. Theses two aspects are expected to drastically improve the performance of the Bulk Si MSM-PDs.

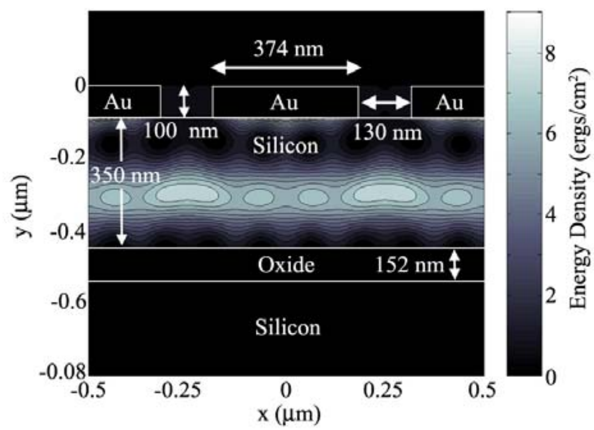

Fig.2 SOI MSM-PD

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Researchers are now starting to look at fabricating MSM-PDs on silicon-on-insulator (SOI) substrates to further improve device performance and to allow for integration with high bandwidth readout integrated circuitry (ROIC) such as transimpedance amplifiers and other circuitry [8,9]. The buried oxide layer isolates carriers that are generated deep in the bulk silicon substrate from the active region of the detector. This aspect of SOI MSM-PDs will improve the bandwidth, noise and bit error ratio (BER) of the device compared to standard bulk-Si MSM-PDs. Also, the contact/Silicon/oxide layers of a SOI can be used to produce a resonant cavity that concentrates the light in the top thin film Si layer [8, 9]. This aspect of SOI MSM-PDs will improve the responsivity compared to the bulk MSM-PD. Hence, the proper use of SOI substrates in MSM-PDs should produce an improvement in the overall device performance, i.e., a combination of high bandwidth and responsivity and low noise. Past works that have tried to use SOI substrates for MSM detectors have vastly oversimplified their analysis resulting in faulty designs. In this paper, we perform a detailed analysis of the optical response of a device with this geometry, taking into account the five resonances mentioned above that occur in these structures. The optical mode used in this application is a VCM mode that couples all of the incident beam into a 1st order diffracted mode that is totally internally reflected by the oxide layer and resonantly amplified by the contact/Si/oxide Fabry-Perot cavity. As mentioned before, HSPs are eliminated, which are undesirable, by the proper choice of the geometry of the structure. The VCM/DM/FPM hybrid mode is shown in Fig. 2. Bandwidth of exceeding 50 Gbit/s and responsivities of 0.40 A/W are achievable with this device.

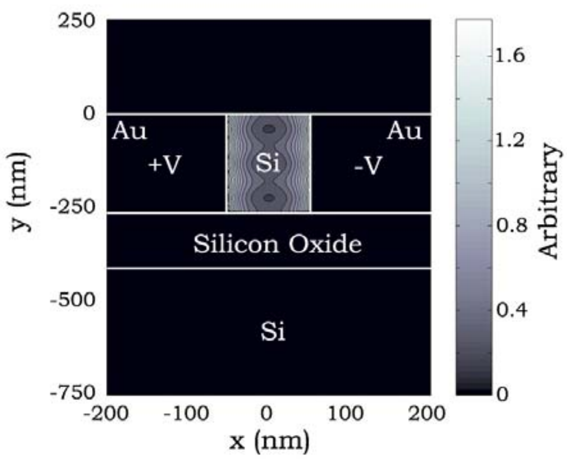

Fig.3 Si APD

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Integrated all-silicon optical receivers have been receiving increased attention because of their widespread use in short-reach 10-Gb/s data communications systems [10]. One type of Si-based structure that has been proposed is silicon-on-insulator (SOI) p-i-n photodiodes and avalanche photodiodes (APD) [11]. In the past work on these structures, the top thin Si layer is not considered for use in the photodetector because of the widely held assumption that the top Si layer is too thin to allow for efficient absorption of 850nm wavelength light. This work analyzes a new type of SOI APD (Fig. 3) with a substantially different structure than the ones studied in the references cited above. For this device, a VCM/FPM hybrid mode is used to localize and concentrate the optical signal between the contacts. The FPM mode is produced by choosing the appropriate thickness for the top Si fingers and buried oxide layer. The geometry of the device is chosen in such as way that WRs, HSPs and diffraction modes do not occur at the wavelength of interest. This device is attractive for APDs because of the uniform electric field between the contacts makes for uniform avalanche effects leading to low bias voltages, reduced noise and reduced timing jitter.

This device is very promising for single photon detectors and other detectors that need higher responsivity than the bulk Si MSM-PD and SOI MSM-PD can achieve. One aspect that is very important is that because of the geometry and uniform field, this device can operate in Geiger mode at an extremely low bias voltage of 10V. Other single photon detectors require much higher operating voltages to operate in Geiger mode. Another aspect of this device that is extremely attractive for a single photon detector is the fact that there will be substantially less timing jitter. In conventional APD structures, the photogenerated carriers typically have to drift $10\mu m$ to the high field region before they are multiplied and collected at the contacts. This leads to a timing jitter of 100ps at an absolute minimum. In the proposed device, the carriers only have to drift 134nm and in the high field region. This will reduce timing jitter to less than 10ps.

3 ELECTRICAL RESPONSE

Once the optical response of the device is performed, it is integrated with four other algorithms in a time-dependent manner to allows the accurate modeling of the performance of the photodetector in a situation that more closely resembles the practical real-world implementation of these devices than has been done by in previous theoretical and modeling work on MSM-PDs. A detailed description of the various algorithms is reported in ref. [7]. Briefly, the algorithm consists of 1) A PRBS generator that produces a 256 random bit sequence (PRBS) 2) A Poisson's Equation solver that calculates the electric field produced by the time independent applied voltage and the time dependent charge distribution within the Si (PESA) 3) A Monte Carlo algorithm (MoCA) that records all data about each charge that is generated by the incident optical signal and calculates trajectories, generation-recombination and photocurrent. 4) An eye diagram and noise analysis (EDNA) algorithm maps the photocurrent into an eye diagram from which ISI and BER information is extracted.

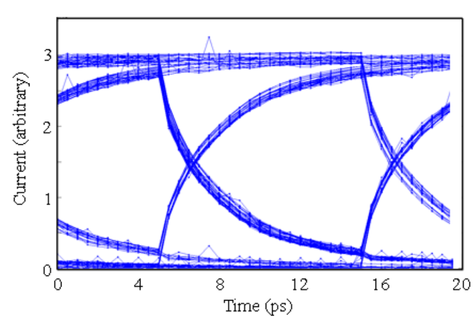

Fig.4 The eye diagram for a Si MSM-PD operating at 100Gb/s with an active layer depth of 0.5μm.

The input signal of the photodetector is modeled as a pseudo-random bit sequence (PRBS) where the bits are either periods when the normal incident, normalized, TM polarized optical signal is incident upon the detector (represented by a "1") and periods of no optical signal (represented as a "0"). The PRBS Algorithm produces a 256 bit PRBS by using a maximum-length shift-register sequence (i.e., m-sequence). The Monte-Carlo Algorithm (MoCA) and the Poisson's Equation Solver Algorithm (PESA) are extensively integrated together in a time dependent way. MoCA describes all aspects of charge-carrier generation, recombination, drift, impact ionization, and induced photocurrent in the electrical contacts. PESA calculates the quasi-static electric field produced by the time independent bias applied across the metal contacts and the time-varying charge density produced by the incident beam. This integrated algorithm progresses in steps in time with the PRBS algorithm turning on or off the incident beam, which produces an electromagnetic field distribution in the Si that is modeled using ExSIBCA; the Poynting vector obtained then is used by MoCA and PESA to calculate the behavior of the photogenerated charge carriers and the quasi-static electric field. The final result is the current vs. time (*i(t)*) plot that will be used by the EDNA algorithm. The EDNA algorithm takes the *i(t)* plot, produces a eye diagram, and calculates the quality factor (Q) and bit error rate (BER). This is a fairly simple algorithm and "folds" back the *i(t)* plot and puts the entire curve into a time duration of a 2 bit period, namely construction an eye diagram.

Fig. 4 shows the eye diagram for Si MSM-PD calculated using the integrated time dependant electrical/optical algorithms mentioned above. The device operates at 100Gb/s with a responsivity (ρ) of 0.06A/W and a very low BER of 10^{-20} for an active layer depth of 0.5μm. There are several different ways to characterize the MSM-PDs but we approached the analysis by setting the bandwidth to a large value of 100Gb/s and evaluating the tradeoff between ρ and BER. The bandwidth of 100Gb/s is higher than any Si MSM-PD device reported to date but is a value that will be of interest in current and future optical communication systems. A different thicknesses of the top active layer Si can be chosen by inducing damage below a certain depth by ion implantation. For an active layer thickness of 6μm we can achieve high ρ (0.25A/W) and high BER 10^{-9}. Only the results of bulk Si MSM-PD electrical response are shown in this paper, however all the modeling techniques used and discussed apply for the MSM-PD on SOI and Si APD.

CONCLUSION

In conclusion, a rigorous method of modeling the performance of various Si based MSM-PD that uses several ERs and OMs to enhance performance are presented. Five modeling algorithms are integrated together in a time-dependent way to model a 256 PRBS of 850nm wavelength TM polarized light, the electromagnetic field distribution in the MSM-PD, quasi-static electric field, the charge carrier motion, and an algorithm to construct eye diagrams and analyze responsivity, inter-symbol interference (ISI) and BER. This work has shown that the metal contacts play a large role in the behavior of Si based MSM-PDs at nanoscale because of the near field effects, electromagnetic resonances, and optical modes they produce. Also, it was shown that improved performances could be achieved by appropriately tapping into these various resonance modes.

There are several items that will need to be addressed for this analysis of ER-enhanced MSM-PDs to be truly complete: the TE polarization behavior, enhanced thermal effects exacerbated by the localization of light, spatial hole burning and device saturation.

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