Modeling of Optoelectronic Devices

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1. Research Target

Signal propagation delay via metal interconnects is becoming a serious problem in realizing high-frequency operation of circuits. The immediate solution is to adopt a large cross-section of metal interconnects, but this hinders high integration of devices in a single chip. Under such a situation, optical interconnects attract much attention [1], which involves light emitting devices, optical waveguides and photodetectors. In order to fully realize optical interconnects, models describing the physical properties of optoelectronic devices become a requirement.

At present, our research group is investigating the response of photodiodes integrated on a Si chip [2,3], which are employed as photodetectors in optical interconnects. We are developing a physics-based model describing the carrier transport characteristics in a photodiode. The model will be useful in predicting photodiode characteristics and performing circuit simulation of optoelectronic integrated circuits (OEICs) [4].

2. Research Results

2.1 Photoresponse of *p-n* Photodiode at High Illumination

We fabricated *p-n* photodiodes using conventional CMOS technology as shown in Fig. 1a. To generate carriers in the depletion region at the *p-n* junction, laser pulses are injected to the n^+ region via the metal layer opening. In our measurement, we used a 532nm-pulsed laser with pulse duration of ~1ns FWHM, an absorption coefficient of ~10^4cm^{-1} and absorption depth of ~1µm into bulk Si. Generated electrons and holes drift to opposite electrodes due to the applied reverse bias and flow out the external circuit as photocurrent. The measurement setup is shown in Fig. 1b. The photocurrent is measured using an oscilloscope. The measured photocurrents are shown in Fig. 2a for different reverse bias voltages. In the low intensity of radiation or the high reverse bias cases, the measured photocurrent keeps the same shape as the irradiated laser pulse, and no time delay is observed. However, by increasing the laser intensity, transport delay becomes clear for low bias conditions. To analyze the measured photocurrent characteristics, 2D device simulations with MEDICI [5], which involve solving the four basic device equations, were performed. Simulation conditions are chosen to be the same as measurement conditions. Simulation results shown in Fig. 2b are similar to the measurements. The apparent transport delay observed for the high laser intensity was found to be due to the high carrier concentration suppressing the potential drop in the depletion region. The highly generated carrier concentration diminishes the field in the depletion region resulting in a reduction of carrier movement. More remarkable observation is that simulated photocurrent shapes for small bias show clear deviation from corresponding measurements. Obvious plateaus occur which are not observed in the measurements. We attribute the reason to the shortcoming of the quasi-equilibrium condition approximated in the 2-dimensional simulator. Such shortcoming originates from the breakdown of the drift-diffusion approximation used in the simulation [3]. Therefore we proposed a necessity of modifying mobility models used in the drift-diffusion approximation at high illumination and low reverse bias condition. This study serves as a foundation to develop a carrier transport model of photodiodes in any operating condition.

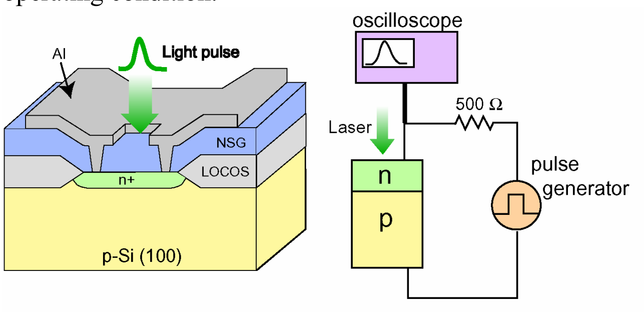

Fig. 1. (a) Cross-section of fabricated *p-n* junction. (b) Setup for measuring photocurrent.

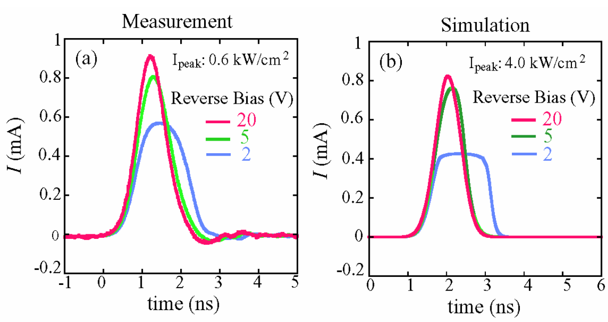

Fig. 2. (a) Measured and (b) MEDICI simulation results of photocurrent for different applied reverse biases.

2.2 Modeling of Vertical *p-i-n* Photodiodes

For the purpose of developing a model for circuit simulation of OEICs, we analytically formulate carrier transport [4] in a vertical *p-i-n* photodiode as shown in Fig. 3. The vertical *p-i-n* photodiode has been discussed by many authors [6], and analytical description has also been developed [7]. However, one important factor, *diffusion* of carriers generated in n^+ and p^+ diffusion region which is used in characterizing the cut-off frequency of the photodiode, has been neglected so far. This factor determines the cut-off frequency in the cases of small load resistance and moderate intrinsic region length. Thus, we take into account the effect of carrier diffusion. We obtained analytical solution for photocurrent in Fourier space, and therefore our formulation is very useful in harmonic balance simulation [8] for circuits. Furthermore, we developed a simulation scheme based on the spectral method [9] for reproducing current in time domain using Fast Fourier Transform (FFT). By using the derived solution in the frequency domain and the scheme, we successfully reproduced the output current (see Fig. 4), which has a comparable accuracy with MEDICI [5] in spite of significant reduction of computational time.

2.3 Cut-Off Frequency of Lateral *p-i-n* Photodiodes

We also investigated lateral *p-i-n* photodiode. This type of photodiode is free from light absorption depth limitation inherent with the vertical type, and thus high responsivity is possible. Moreover, the technology is compatible to VLSI processes. For our purpose, we fabricated a Si lateral *p-i-n* photodiode as shown in Fig. 5.

Figure 6a shows measured output photocurrent, from which reverse bias dependence can be found. Figure 6b shows results transformed to frequency domain of the photoresponse. The input is a Gaussian laser pulse of ~60ps FWHM. We confirmed ~1GHz cut-off frequency of the fabricated device in Fig. 6b.

To clarify the cause of the tail part (in Fig. 6a) which determines the cut-off frequency, we performed numerical simulation using MEDICI [5]. Changing the *n*+ and *p*+ diffusion depth from 0.1μm to 5μm, we confirmed the reduction of the tail part as shown in Fig. 7. Therefore short intrinsic region length, large reverse bias, and deep diffusion depth are necessary factors for achieving high cut-off frequency photodetectors [10]. This study is useful for developing a model of carrier transport in the lateral *p-i-n* photodiodes

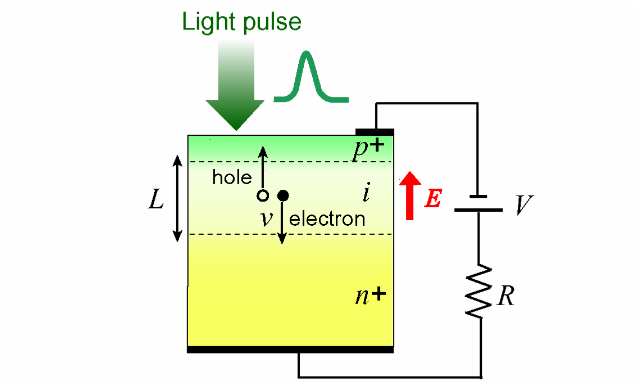

Fig. 3. Structure of a vertical *p-i-n* photodiode.

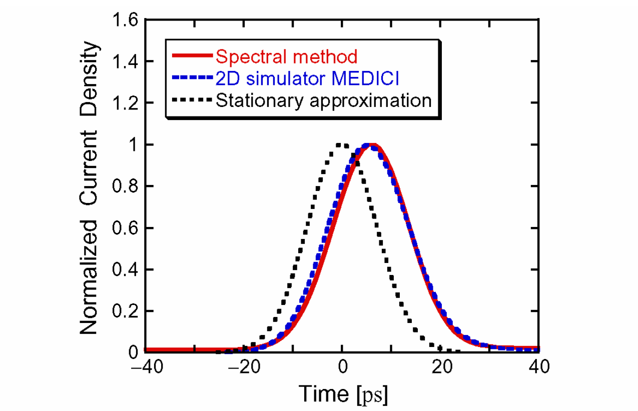

Fig. 4. Photocurrent calculated by our model in comparison with MEDICI and stationary approximation. The model is in excellent agreement with MEDICI.

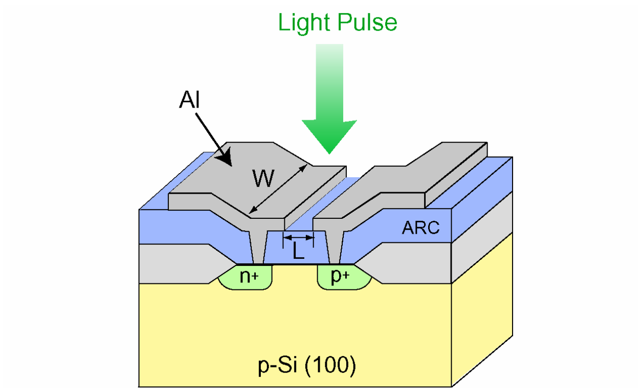

Fig. 5. Structure of a fabricated lateral *p-i-n* photodiode.

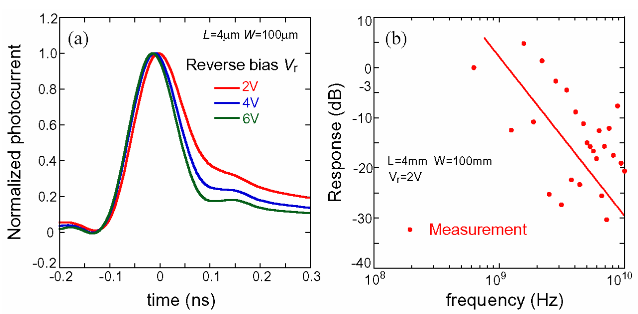

Fig. 6. (a) Measured photocurrent of the lateral *p-i-n* photodiode. (b) The cut-off frequency of the fabricated photodiode is extracted to be ~1GHz.

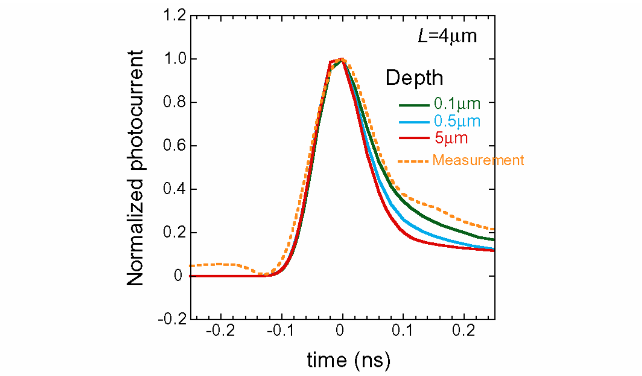

Fig. 7. MEDICI simulation of photocurrent for different diffusion depths. The tail reduces as the diffusion depth is increased.

3. Research Results

We have investigated photoresponse of photodiodes theoretically and experimentally. Through the experiment for a *p-n* photodiode at high illumination, we clarified carrier transport in which the ordinary drift-diffusion approximation is not appropriate. Furthermore, we suggested a necessity of modifying present mobility models if we use the framework of the drift-diffusion approximation. We also perform a measurement of photocurrent for lateral *p-i-n* photodiodes. From this work, the causes of the end tail in the measurements are investigated. The important features of the carrier transport are useful for modeling such devices. We also developed a model describing carrier transport in the vertical *p-i-n* photodiodes. In particular, we considered the diffusion of carriers generated in the n^+ or p^+ region, which has been neglected so far. The photocurrent calculated by our model in time domain shows excellent agreement with the result obtained by using 2-dimensional device simulator MEDICI. Our model is useful for performing circuit simulation of OEICs employing vertical type of *p-i-n* photodiodes

4. Future Work

We will develop models describing the carrier transport in the *p-n* and the lateral *p-i-n* photodiodes, based on the experimental studies we have carried out. The lateral *p-i-n* photodiodes have significant features over the vertical one since the carrier moving path is perpendicular to light absorption direction. Thus, it does not suffer from limitations due to light absorption length. With this feature, it enables both high responsivity and high speed device operation. Furthermore, it realizes fabrication of silicon monolithic photodetectors since the technology is compatible to VLSI processes. Finally we are aiming at performing circuit simulation of OEICs using the developed models in this work.

References

[1] See, for example, L. C. Kimerling, Appl. Surf. Sci. **159**, 8 (2000).
[2] O. Matsushima *et al.*, Semicond. Sci. Tech. **19**, S185(2004);
[3] K. Konno, *et al.*, Appl. Phys. Lett. **84**, 1398(2004).
[4] K. Konno, *et al.*, Submitted to J. Appl. Phys.
[5] MEDICI User's Manual Synopsys (2002).
[6] Y. Leblebici, *et al.*, J. Lightw. Tech. **13**, 396 (1995); P. S. Matavulj *et al.*, J. Lightw. Tech. **15**, 2270 (1997) and reference therein.
[7] R. Sabella, S. Merli, IEEE J. Quant. Electron. **29**, 906 (1993); G. Toresse *et al.*, Microw. Opt. Tech Lett. **31**, 329 (2001) and reference therein.
[8] K. S. Kundert, A. Sangiovanni-Vincentelli, IEEE Trans. CAD-**5**, 521 (1986).
[9] See, for example, B. Mercier, *An Introduction to the Numerical Analysis of Spectral Methods* (Springer-Verlag, Berlin, 1989).
[10] O. Matsushima, Master Thesis (Hiroshima University, Febrary, 2003)

5. Papers and Presentation

① Refereed Journals

1. O. Matsushima, K. Konno, M. Tanaka, K. Hara, M. Miura-Mattausch, "Carrier Transport in Highly Generated Carrier Concentration", Semicond. Sci. Tech. **19**, S185 (2004)
2. K. Konno, O. Matsushima, D. Navarro, M. Miura-Mattausch, "Limit of Validity of the Drift-Diffusion Approximation for Simulation of Photodiode Characteristics", Appl. Phys. Lett. **84**, 1398 (2004)
3. K. Konno, O. Matsushima, D. Navarro, M. Miura-Mattausch, "High-Frequency Response of *p-i-n* Photodiode Analyzed by an Analytical Model in Fourier Space", Submitted to J. Appl. Phys.

② Presentation

1. O. Matsushima, K. Konno, M. Tanaka, K. Hara, M. Miura-Mattausch, "Carrier Transport in Highly Generated Carrier Concentration", International Conference on "Nonequilibrium Carrier Dynamics in Semiconductors", Modena, Italy, July 28-Aug 1, 2003.
2. K. Konno, O. Matsushima, K. Hara, G. Suzuki, M. Miura-Mattausch, "Modeling of Photoresponse of *p-i-n* Photodiodes and Current Simulation based on the Spectral Method", Japan Society of Applied Physics, 2004 Spring Meeting