Analysis and Modeling of Carrier Transport in Photodiodes

Kohkichi Konno (COE Researcher),
Mitiko Miura-Mattausch (Prof., Graduate School of Advanced Sciences of Matter)

1. Research Target

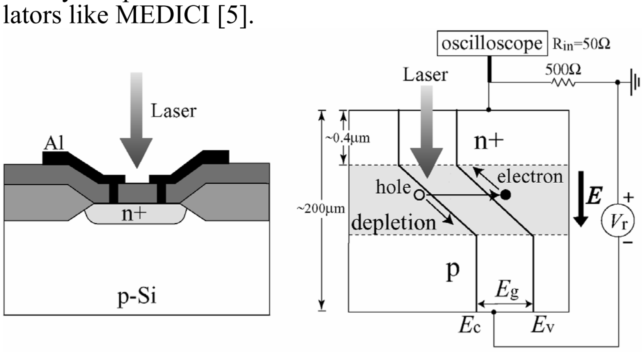
Device dimension in LSI is continuously being reduced to obtain high integration and high frequency operation. However, interconnection propagation delay using metal interconnects overwhelms transistor gate delay [1]. This impedes realization of fast switching circuit operation. Under such a situation, optical interconnection becomes an attractive option [1], which involves light emitting devices, optical waveguide and photodetectors. In order to design optoelectronic integrated circuits (OEICs), models describing the electronic and optical characteristics of optoelectronic devices for circuit simulation become a necessity. To model such characteristics correctly, physical understanding of carrier transport in optoelectronic devices is necessary. In this research work, we focus on the photodiode as an optoelectronic device. We investigated carrier transport characteristics in photodiode and developed an analytical model necessary for high frequency operation [2,3,4].

2. Research Results

2.1 Carrier Transport Feature in Photodiodes at High illumination

In our recently published works [2,3], we investigated the photoresponse of a Si *p-n* photodiode both experimentally and theoretically.

For the theoretical approach, two numerical calculation methods are generally considered. One is the Monte-Carlo simulation, and the other is to solve consistently the closed system of equations composed of the Poisson equation, the continuity equation, and the current-density equation based on the drift-diffusion (DD) approximation. Since the former simulates the transport of each carrier, it needs a very long computational time. On the other hand, as for the latter, the computational cost is significantly reduced because the complexity of microscopic processes is eliminated by introducing the mobility parameter. Therefore, this method is very practical and widely adopted in commercial 2-dimensional device simulators like MEDICI [5].



(a) (b)

Fig 1 (a) Structure of the *p-n* photodiode. (b) Schematic of the experimental setup.

In the DD approximation, the most important factor is mobility, because a correct solution for carrier transport can be obtained for an appropriate mobility model. We note that the condition for the DD approximation is realized in quasi-equilibrium situations. In the photodiode, however, such quasi-equilibrium situations are not exactly true, but rather a fully non-equilibrium condition is expected since reverse bias is applied. Therefore, it is important to clarify the condition when the DD approximation is applicable in investigating the photodiode response.

We performed an experiment as shown in Fig. 1 using a fabricated Si *p-n* photodiode and a 532nm-pulsed laser with pulse duration of ~1ns FWHM. The left-hand side in Fig. 2 shows the measured photocurrents. We also reproduced the results shown in the right-hand side in Fig. 2, using MEDICI [5] under the same condition as the experiment. At low laser intensity, the experimental results coincide well with those obtained by using the simulator. On the contrary, at high laser intensity, we find appreciable discrepancy in the signal waveforms between the experiment and the simulation. It is very interesting to note that the results obtained by MEDICI show plateau-like forms. The plateaus cannot be eliminated even if the mobility model in the simulation is changed.

We concluded via order estimates that the cause of the plateau is due to the space charge limitation effect [6]. The DD approximation is implicitly assumed for the derivation of the conventional space-charge-limited current [6]. This result means that the DD approximation is not precise for the case of high photo-generated carrier density with low reverse bias. Furthermore, our conclusion is proved by numerical calculations for carrier dynamics inside the device.

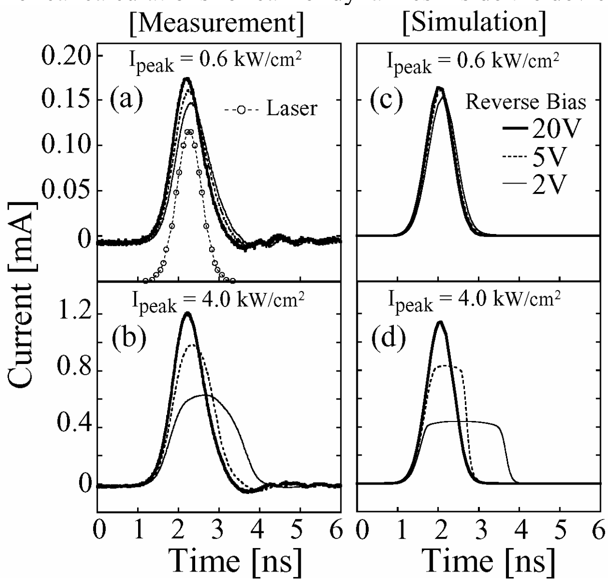


Fig 2 Comparison between measurement and numerical simulation by MEIDCI.

From this work, we suggested a necessity of a modifying mobility models in order to simulate the photodiode response more accurately in the framework of the DD approximation.

2.2 Modeling of Carrier Transport in Vertical *p-i-n* Photodiodes

In order to design OEICs, accurate physics-based models describing the characteristics of optoelectronic devices are necessary. One such device is the *p-i-n* photodiode, which has been generally investigated using two approaches: full numerical approach [7] and analytical approach [8]. For models employed in circuit-simulation, the latter is more appropriate because the computational time is considerably reduced, and thus adopted here.

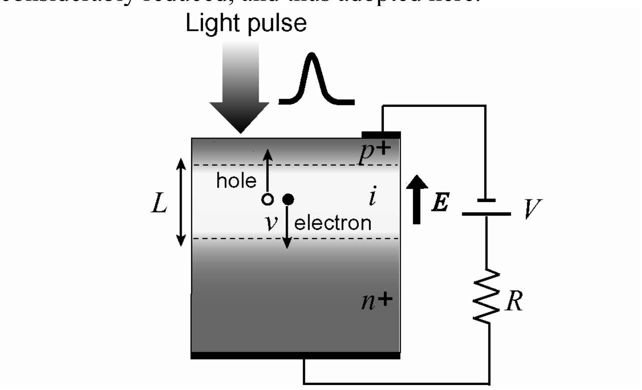


Fig 3 Structure of the vertical *p-i-n* photodiode.

We particularly investigated a vertical *p-i-n* photodiode as shown in Fig. 3. The high frequency response of the photodiode is mainly limited by three factors: (1) drift transit time for carriers to cross *i*-region, (2) *RC* constant, (3) diffusion time. The first and second factors are discussed precisely in Ref. [8]. However, the third factor is often neglected in analytical formulations and its effect on high frequency response is not investigated yet. The diffusion becomes dominant and determines the cut-off frequency in certain cases (see Ref. [4] for details).

In our recent paper [4], we presented a consistent formulation for the current characteristics of the vertical *p-i-n* photodiode by taking into account the carrier diffusion generated in the n^+ or p^+ region. Furthermore, we developed a simulation scheme based on the spectral method [9] to express photocurrent in time domain. In spite of significant reduction in calculation time, accuracy of our calculation results is comparable to those of the conventional 2-dimensional numerical device simulator MEDICI as shown in Fig. 4. Our formulation is very easy to use and compatible especially to the harmonic balance simulation [10] of circuits. Therefore, our result is very useful in performing circuit simulation of OEICs.

3. Summary

We investigated the photoresponse of *p-n* photodiodes at high illumination and elucidated carrier transport characteristics which cannot be described by present mobility models. A necessity of modifying present mobility models is suggested [2,3]. Furthermore, we developed a model of carrier transport in the vertical *p-i-n* photodiode, which has a computational accuracy comparable to a 2-dimensional device simulator [4]. Our model is very useful in performing circuit simulation of OEICs.

4. Future Work

Future research work will consider the lateral-type *p-i-n* photodiode. This type has a high responsivity since light absorption length should no longer be considered during operation. Moreover, the technology is compatible with VLSI processes. At present, we are developing a model for describing the carrier transport feature in this type of photodiode. Moreover we are planning to realize circuit simulation of OEICs with such photodiodes.

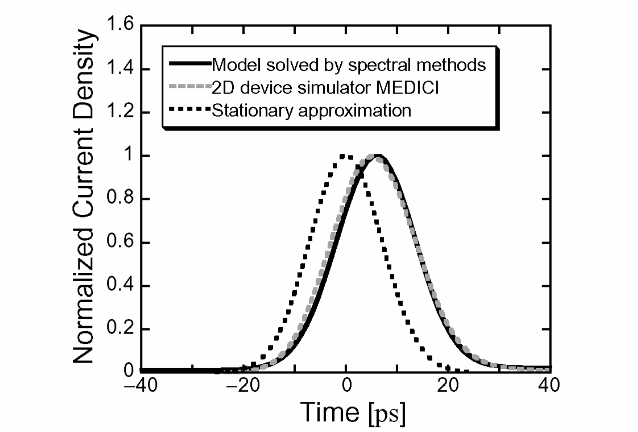


Fig 4 Accurate calculation of the photocurrent using the developed model.

References

[1] 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] See, for example, A. Rose, Phys. Rev. **97**, 1538 (1955).

[7] See, for example, P. S. Matavulj *et al.*, J. Lightw. Tech. **15**, 2270 (1997).

[8] 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.

[9] See, for example, B. Mercier, *An Introduction to the Numerical Analysis of Spectral Methods* (Springer-Verlag, Berlin, 1989).

[10] K. S. Kundert, A. Sangiovanni-Vincentelli, IEEE Trans. CAD-**5**, 521 (1986).

5. Papers and Presentation

5.1 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-Mattsusch, "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-Mattsusch, "High-Frequency Response of *p-i-n* Photodiode Analyzed by an Analytical Model in Fourier Space", Submitted to J. Appl. Phys.

5.2 Presentation

1. 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.