Extended Abstracts of the 1992 International Conference on Solid State Devices and Materials, Tsukuba, 1992, pp. 199-201

A Novel Contactless and Nondestructive Measurement Method of Surface Recombination Velocity on Silicon Surfaces by Photoluminescence

Toshiya SAITOH, Youichiro NISHIMOTO, Takayuki SAWADA and Hideki HASEGAWA

Research Center for Interface Quantum Electronics and
Department of Electrical Engineering
Hokkaido University, Sapporo, 060, Japan
Telefax:011-707-9750, Phone:011-716-2111 ext.6873 or 6519

The surface recombination velocity, S, is usually taken to be a characteristic constant of the surface. However, we have recently shown that S is strongly dependent on the incident light intensity.

This paper presents a novel photoluminescence(PL)-based measurement method of S. By this method, the value of S under device operation conditions can be determined in a contactless and non-destructive fashion together with the energy distribution of the density (N_{ss}) of the surface states causing recombination. The measurement principle and method of the new technique are presented as well as its application to bare and passivated Si surfaces.

1. INTRODUCTION

The surface recombination process plays important roles in determining the performance of solar cells and optoelectronic devices. It is commonly described by the surface recombination velocity, S. S is usually taken to be a characteristic constant of the surface. However, as we have shown recently[1], it is strongly dependent on the measurement conditions as well as the semiconductor bulk properties. For example, high quality Si-SiO_2 interfaces usually give values of S in the range of 0.1-10 cm/s when measured in the generation mode by the standard MOS method[2]. However, the same surface exhibits a much larger S of 10^3-10^4 cm/s in the recombination mode under normal solar cell operation condition[1]. Thus, knowledge of the value of S under realistic conditions of device operation is essential for device modeling, design and characterization.

This paper presents a novel photoluminescence(PL)-based measurement method of S. By this method, the value of the effective surface recombination velocity, S_e, under device operation conditions can be determined in a contactless and non-destructive fashion together with the energy distribution of the density of the surface states causing recombination.

In this paper, the measurement principle and method of the new technique are presented. The applicability of the present method was demonstrated by applying it to bare and passivated silicon surfaces in view of solar cell applications.

2. PRINCIPLE OF THE NEW METHOD

Surface recombination velocity, S, is known to be one of the most important parameters which determine the band edge photoluminescence(PL) intensity. Thus, the PL intensity, I_{PL}, is usually extremely surface sensitive. However, the relationship between S and I_{PL} is not well established.

Under the assumptions that the surface recombination is the predominant recombination process and that the excitation light is not so strong as to modify the majority carrier concentration, one can derive the following simple relation for an n-type semiconductor.

$$S = C\, N_D \,/\, (I_{PL}/\phi) \qquad (1)$$

where N_D is donor density, ϕ is the excitation intensity and C is a constant which depends on geometrical arrangements, reflection coefficient of the surface, the minority carrier diffusion length etc. S in the above expression is the effective surface recombination velocity evaluated at the edge of the surface depletion and accumulation layer rather than the actual surface itself.

Thus one sees from Eq.(1) that not the PL intensity itself but the PL efficiency defined by I_{PL}/ϕ, is related to S. The usual assumption of a constant S corresponds to the situation where I_{PL} is proportional to ϕ. However, as both of our previous theory[3] and measurements have demonstrated, I_{PL} is not proportional to ϕ, which means that the value of S is not a constant of surface. This variation of S with ϕ is caused by the fact that the surface band bending, separation of quasi Fermi levels and amount of surface state charge change with

the change of the numbers of excited charges.

Thus, the value of S can be evaluated by analyzing the dependence of PL efficiency on ϕ. The plot of the dependence of PL efficiency on ϕ is hereafter referred to as the PL efficiency spectrum. Figure 1 schematically shows the behavior of a typical PL efficiency spectrum. The PL efficiency spectrum consists of three distinct regions. Among them, the transition region between dark pinning region and the radiative or Auger recombination limited region, is most important to obtain information concerning the surface recombination. For example, it can be shown that the slope of the PL efficiency spectrum in the transition region and the photon flux density ϕ_0 causing this transition, give the distribution shape and magnitude of the surface or interface state density, N_{ss}, respectively.

3. THEORETICAL CALCULATION OF SURFACE RECOMBINATION VELOCITY AND PHOTOLUMINESCENCE INTENSITY

Since the assumptions to derive Eq.(1) do not hold generally and the physical processes involving changes of the surface band bending, separation of quasi Fermi levels and amount of surface state charge, are extremely complicated, the analysis of the PL efficiency spectra has to be done on computer. For this purpose, the previously developed one dimensional Scharfetter-Gummel type vector matrix simulation program[1] was used. It includes SRH surface recombination process through surface state continuum, presence of surface fixed charge, bulk SRH recombination, and bulk radiative and Auger recombinations.

Figure 2 shows an example of the calculated behavior of S_e and PL efficiency spectra for an n-type Si surface having discrete, uniform or U-shaped N_{ss} distribution. It is clearly seen that the behavior of S_e and PL efficiency spectra depend strongly on the N_{ss} distribution shape. The mechanism responsible for this difference is schematically shown in Fig.3. For the discrete states, the number of states participating the recombination becomes constant, as soon as the the quasi Fermi levels are amply split by the excitation light. On the other hand, the number of states participating recombination increases with the split of quasi Fermi levels for continuous distributions. Thus, more photons are required to shift quasi Fermi levels through continuous surface states than the discrete surface state.

By fitting calculated PL efficiency spectrum to experimental data, one can determine the values of S as a function of ϕ as well as the N_{ss} distribution causing recombination.

4. APPLICATION OF Si WAFERS

For the measurement of the PL efficiency

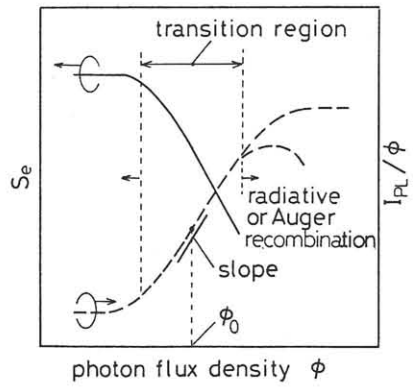

Fig.1 Behavior of S_e and I_{PL}.

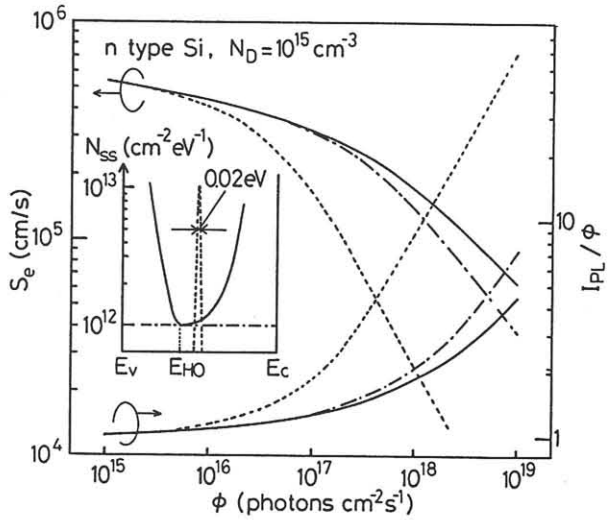

Fig.2 Calculated behavior of S_e and I_{PL}.

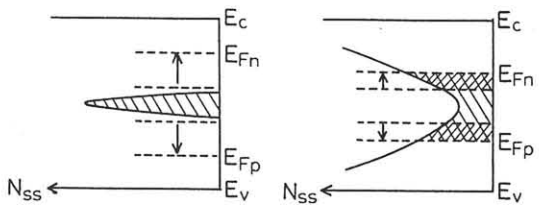

Fig.3 Split of quasi Fermi levels and states causing recombination.

spectra, an automatic PL measurement system shown in Fig.4 was used. Ar^+ laser light (514.5nm) was used as the excitation source and the excitation intensity was automatically changed by the computer controlled ND filters.

Examples of the measured PL data and determined S_e are shown in Fig.5 for unpassivated and passivated n-type Si wafers. Surface of unpassivated sample was treated by HF. For passivation, oxidation was done in dry O_2 at 1000 °C for 2 hours. By fitting the experimental PL efficiency data to theory, it was found that the surface states have U-shaped N_{ss} distributions. It is seen in Fig.5 that the value of S_e is a strong function of ϕ, giving reasonable values of 20,000 cm/s and 2,000 cm/s for unpassivated and passivated Si surfaces, respectively,

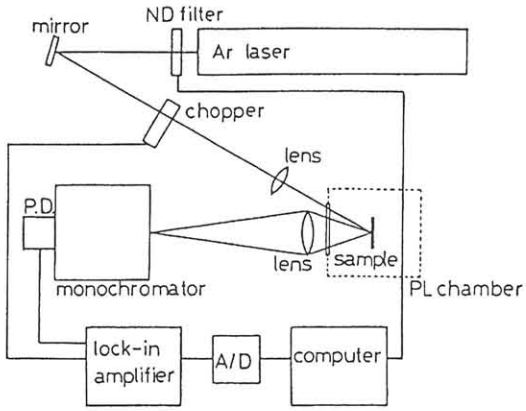

Fig.4 Experimental set-up.

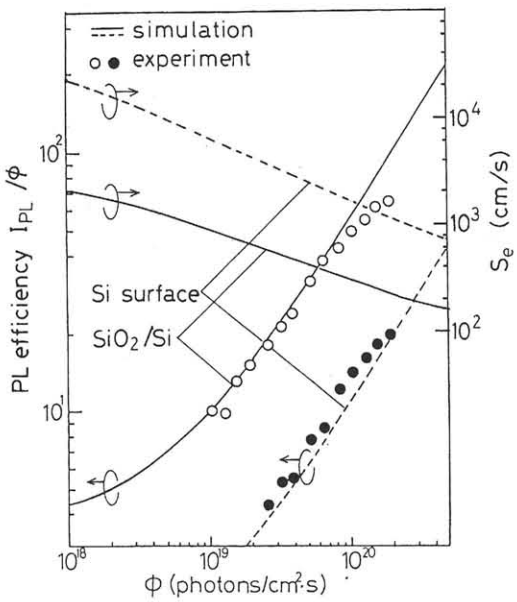

Fig.5 Measured PL efficiency and determined S_e for unpassivated and passivated Si surface.

under 1 sun condition. Figure 5 also shows that the value of S_e is considerably reduced under concentrated sunlights. Figure 6 shows an example of the determined N_{ss} distribution on bare Si surface whose determination was impossible previously. The observed PL line shape is also shown in the inset.

5. SUMMARY

A novel photoluminescence(PL)-based measurement method of the surface recombination velocity, S, was presented. It was shown that this method can determine the value of S under device operation conditions as well as the energy distribution of the density of the surface states causing recombination.

The present method was applied to bare and passivated Si surfaces in view of solar cell applications. It was shown that the value of S_e is a strong function of ϕ, giving reasonable values of 20,000 cm/s and 2,000 cm/s for

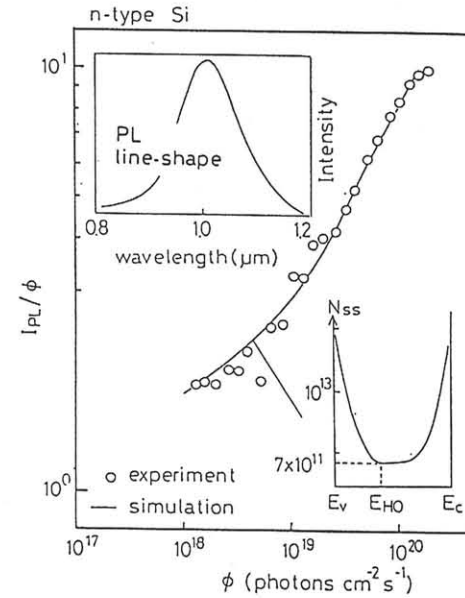

Fig.6 Determined N_{ss} distribution on bare Si surface.

unpassivated and passivated Si surfaces, respectively, under 1 sun condition. N_{ss} distributions on bare and passivated Si surface were found to be both U-shaped.

As compared with the previous methods of S measurement including the MOS method[2], the photo-decay method (wafer τ)[4] and the frequency modulated photo-current method[5], the new method has the following advantages:

(a) It provides values of S under the device operation conditions.
(b) It is contactless and directly applicable to wafers as well as to intermediate processing steps.
(c) It is non-destructive.
(d) It requiring a simple and standard set-up.
(e) It simultaneously determines the N_{ss} distribution causing surface recombination.

ACKNOWLEDGMENT

This present work was financially supported by a Research Grant from Sunshine Headquarter and a Research Grant from PVTEC Organization.

REFERENCES

1)T.Saitoh and H.Hasegawa: Jpn.J.Appl.Phys. 29 (1990) L2296.
2)A.S.Grove and D.J.Fitzgerald: Solid-State Electron. 9 (1966) 783.
3)T.Saitoh, H.Iwadate and H.Hasegawa: Jpn.J. Appl.Phys. 30 (1991) 3750.
4)A.Usami and T.Kushida: Oyo Butsuri 50 (1981) 607.
5)E.Suzuki and Y.Hayashi: IEEE Trans. Electron. Devices ED-36 (1989) 1150.