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Computer Analysis of Surface Recombination Process at Si and Compound Semiconductor Surfaces and Behavior of Surface Recombination Velocity

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1. Introduction

Surface recombination at semiconductor surfaces and interfaces is known to cause various unwanted effects in the operation of electronic and optoelectronic devices such as HBTs, LEDs, photodetectors and solar cells. It is usually described in terms of the so-called "surface recombination velocity" which is assumed to be a characteristic constant of the surface or interface.

Contrary to this, our group has recently made rigorous calculations of surface recombination at semiconductor surfaces [1-3] and has shown, for the first time, that the surface recombination velocity for a given surface state distribution is not a constant, but is a strong function of conduction type, doping, fixed surface charge and minority carrier injection level. However, previous analysis of our group was done only on specific cases of Si solar cell surfaces and various GaAs surfaces with special surface treatments. Thus, general behavior of surface recombination velocity was not amply clarified at all.

The purpose of this work is to perform an extensive analysis of surface recombination on Si and III/V surfaces to clarify and understand the behavior of the surface recombination velocity over a wide range of the level of minority carrier photo- and current-injection for various surface state density distributions, and for wide range of initial band bending induced by the surface fixed charge Q_{FC}.

2. Computer Simulation Procedure

Rigorous numerical calculations of the effective surface recombination velocity for Si and III/V semiconductors were made using a one-dimensional Scharfetter-Gummel-type vector matrix program developed by Saitoh et al [1]. The program solves self-consistently the Poisson's and continuity equations taking account of bulk radiative, Shockley-Read-Hall (SRH) and Auger recombinations in addition to surface recombination based on the SRH statistics. Both discrete and continuous surface state distributions were considered. For the latter, a U-shaped surface state distribution in accordance with the Disorder Induced Gap States (DIGS) model [4] was assumed. It consists of donor- and acceptor-like type states which are divided by the charge neutrality level E_{HO}.

3. Results and Discussion

As representative examples of the result of the present analysis, calculated behavior of the effective surface recombination S_{eff} under photo-injection by Ar^+ laser light ($h\nu$=2.4 eV) is shown in Figs. 1-3 for a typical thermally oxidized n-type Si surface and a CVD SiO_2 passivated n-type GaAs surface. Here, S_{eff} is defined as the surface recombination rate U_S divided by the minority carrier concentration at the depletion or accumulation layer edge.

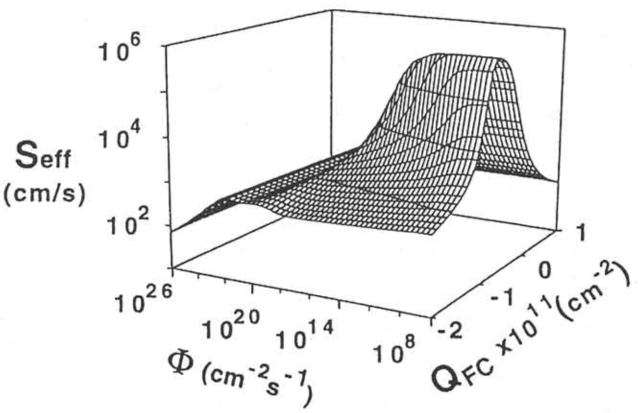

Fig.1. Effective surface recombination velocity S_{eff} vs. photon flux density Φ and surface fixed charge density Q_{FC} for n-Si

Figure 1 presents a 3D plot of S_{eff} versus the incident photon flux density ϕ and surface fixed charge density Q_{FC} calculated for Si. A qualitatively similar plot has been obtained for GaAs. The dependencies of S_{eff} as a function of ϕ and the surface Fermi level position in the dark E_{FO}, corresponding to band bending induced by Q_{FC}, are shown in Figs. 2 and 3, respectively.

From such extensive analysis, as shown in Figs. 1-3, the following properties of the effective surface recombination velocity became clear.

(1) S_{eff} depends strongly on both the excitation intensity and surface band bending induced by Q_{FC}. The changes in S_{eff} vs. ϕ are 4 orders of magnitude for the thermally oxidized Si surface and 5 orders for the passivated GaAs surface at the depleted and weakly inverted surfaces (Figs. 2a and 3a). The usual assumption of a constant S_{eff} is totally incorrect except for some special regions.

(2) S_{eff} drops dramatically at high injection levels and this is primarily due to saturation of the surface states as the SRH recombination centers. The slope for this drop is unity for discrete states and becomes less than unity for continuous states.

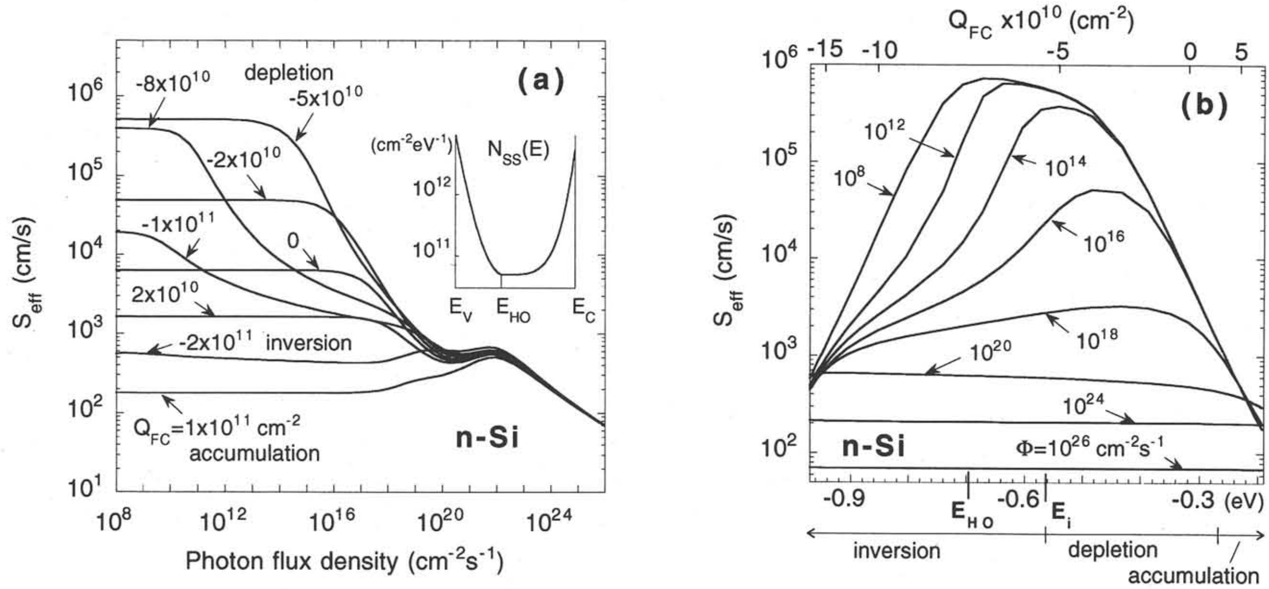

Fig.2. Effective surface recombination velocity vs. photon flux density (a) and surface Fermi level position in the dark (b) for Si. $N_{SS}=N_{SSO}\exp((E-E_{HO})/E_0)^n$, where $N_{SSO}=5\times10^{10}$ $cm^{-2}eV^{-1}$, E_{HO} =-0.69 eV below E_C, E_0=0.17 eV (donor), 0.48 eV (acceptor), n=1.8 (donor), 4.5 (acceptors), capture cross section for holes $c_p=10^{-15}$ cm^2 and for electrons $c_n=10^{-14}$ cm^2, respectively.

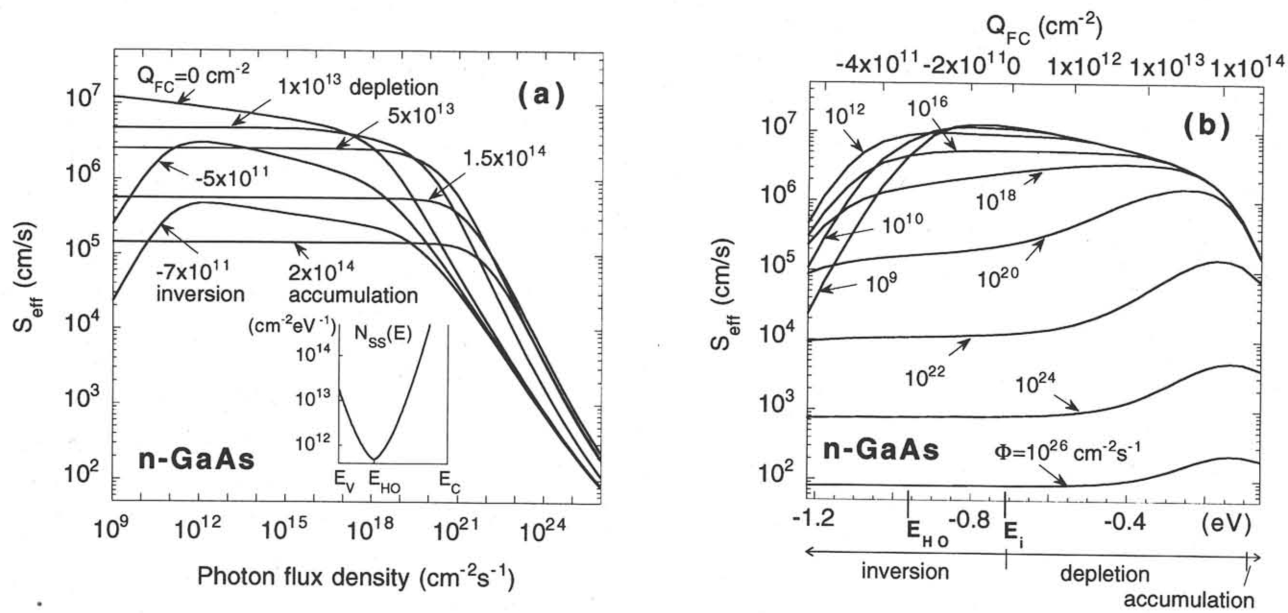

Fig.3. Effective surface recombination velocity vs. photon flux density (a) and surface Fermi level position in the dark (b) for GaAs. $N_{SS0}=5\times10^{11}$ $cm^{-2}eV^{-1}$, E_{H0} =-0.96 eV, E_0=0.2 eV (donor, acceptor), n=1.5 (donor, acceptor), $c_p= c_n=10^{-16}$ cm^2, respectively.

(3) S_{eff} approaches its maximum value under strong depletion and weak inversion conditions when $n_S \approx p_S$ is realized. However, the amount of Q_{FC} to realize this condition depends strongly on the injection level due to a change in band bending and splitting of quasi-Fermi levels caused by injection. Difference in the position of the charge neutrality level E_{HO} greatly affects the behavior and leads to difference seen between Fig.2 and Fig.3. In the case of the GaAs surface, S_{eff} can go up to the carrier thermal velocity of about 10^7 cm/s due to high densities of surface states.

(4) Surface recombination can be significantly reduced by shifting the surface Fermi level E_{FO} towards band edges by introducing appropriate amount of fixed charge. For example, S_{eff} on the Si surface can be decreased down to the values of about 10^2 cm/s by the positive surface fixed charge of 10^{11} cm^{-2} inducing accumulation or larger negative Q_{FC} inducing inversion.

References

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