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Measurement of the Surface Recombination Velocity S at the Si–SiO$_2$ Interface by the Dual-Mercury Probe Method

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A novel measurement technique of the surface recombination velocity S at the Si-SiO$_2$ interface by the dual-mercury probe method is proposed. It is shown that the S experimentally obtained has the pyramid-like peak from near flat-band to midgap condition and takes an extremely low value less than 10 cm/s at both inversion and accumulation condition. In addition, the S is compared with the interface-state density D_{it}.

1. Introduction

The thermally grown Si-SiO$_2$ interface is the essential material system for many Si devices. Numerous characterization techniques for the interface are generally concerned with the measurement of the majority-carrier properties[1]. For minority-carrier devices such as a solar cell, it is important, however, to understand the properties of minority carriers, e.g., electron-hole recombination at the interface. The recombination is usually characterized by a surface recombination velocity S, that corresponds to a minority-carrier lifetime τ in the Si bulk. The S expressed by the Shockley-Read-Hall (SRH) statistic is a complex function of Si-SiO$_2$ interface properties, i.e., the density and capture cross section of Si-SiO$_2$ interface states, and surface carrier densities[2]. Therefore, a technique to experimentally determine the S must be required. To our knowledges, very few works have been reported so far[3)-4)].

In this paper, a novel measurement technique of the S at the Si-SiO$_2$ interface based on the dual-mercury probe method[5),6)] is described. It is shown that the S at different Si-SiO$_2$ interfaces is successfully evaluated as a function of a gate bias voltage. The experimental results are investigated, comparing with the interface-state density D_{it}.

2. Experimental and analytical method

2.1 Measurement setup and samples

The measurement setup for the evaluation of S is schematically shown in Fig.1. Two mercury probes (0.5mmϕ, space:5mm) made contacts with the HF-etched back surface of the oxidized Si wafer sample through a Mylar orifice plate by vacuum-pumping through a little gap between the Mylar plate and the wafer.

The measured samples were n-type, (100)-oriented, 17-22Ω-cm, FZ Si wafers, oxidized in dry O$_2$ (SiO$_2$~800A) and followed by evaporation of Indium Tin Oxide (ITO) films as transparent gates. One sample was annealed in O$_2$ at 800℃ for 30min before the ITO evaporation. Another sample was annealed in H$_2$ at 400℃ for 30min after the dry O$_2$ oxidation and ITO evaporation to reduce the

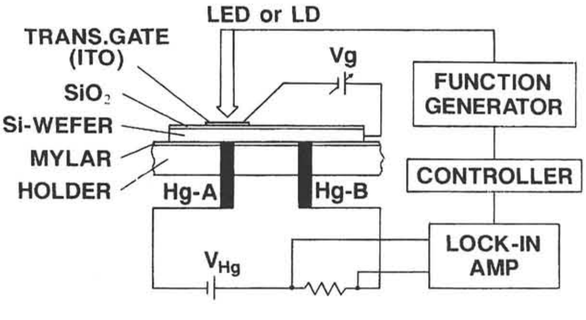

Fig.1 Schematic measurement setup for the dual-mercury probe method for the evaluation of the surface recombination velocity S at the Si-SiO$_2$ interface.

Si-SiO$_2$ interface-state density.

The intensity-modulated light (GaAs LED: 3mW) illuminated the ITO gate to generate minority carriers near the Si-SiO$_2$ interface. One Hg probe situated beneath the ITO gate was reversely biased to collect a part of photo-generated minority carriers diffused from the vicinity of the Si-SiO$_2$ interface. A gate voltage was applied to change surface band vending. The DC bias light of a W-lamp (50 mW/cm^2) also illuminated the whole front surface of the sample to reduce the resistance of the measurement circuit. The frequency-dependent photocurrent was measured as a function of gate bias voltage by using a 100kHz lock-in amplifier. To determine the τ and D of the sample, the similar measurement of the photocurrent was also performed at the sandblasted surface. The interface-state density D_{it} of each sample was estimated by the quasi-static and high-frequency C-V measurement.

2.2 Evaluation procedures of the surface recombination velocity S

The evaluation of the τ and D of minority carriers in the Si wafer using the dual-mercury probe method has been presented previously in detail$^{5)}$ and will therefore only be reviewed here. The behavior of the photo-generated minority carriers is approximately dealt with to be one-dimensional for brevity. Because the applied DC bias appears mainly in the depletion region of the reversely biased Hg contact. In such a case, the photocurrent picked up by the Hg contact is expressed as a solution of continuity and diffusion equations with adequate boundary conditions$^{7)}$ and is a complicated function with three unknown parameters, τ, D, and S. One way to simplify the analytical solution is to eliminate one of these parameters. It has been shown that, for S higher than around 10^6 cm/s, the normalized photocurrent is independent on the value of S$^{5)}$. We adopt this limited case for the evaluation of τ and D by measuring the sandblasted surface of the wafer sample. For the case of $W/L>3$ and $\omega\tau \gg 1$, where $L=\sqrt{\tau D}$ and ω is an angular frequency, τ and D have been shown to be able to be graphically determined from the simplified analytical formula$^{5)}$. However, even for the other cases, we can obtain τ and D by curve-fitting with the aid of calculated correction factors. After the determination of τ and D, the dependence of the photocurrent on S can be calculated as a function of modulation frequency. Then the S at given surface on the wafer sample can be evaluated by comparing the experimental data with the corresponding calculations. In other words, the proposed technique makes it possible to determine τ and S separately. The accuracy of the determined S is generally improved for a wafer sample with longer minority-carrier lifetime and/or larger thickness. The above-mentioned procedures were used for the evaluation of the S at the Si-SiO$_2$ interfaces as a function of the gate bias voltage.

The energy distribution of the Si-SiO$_2$ interface-state density D_{it} was measured by a conventional quasi-static and high-frequency C-V method to compare it with the experimentally obtained S.

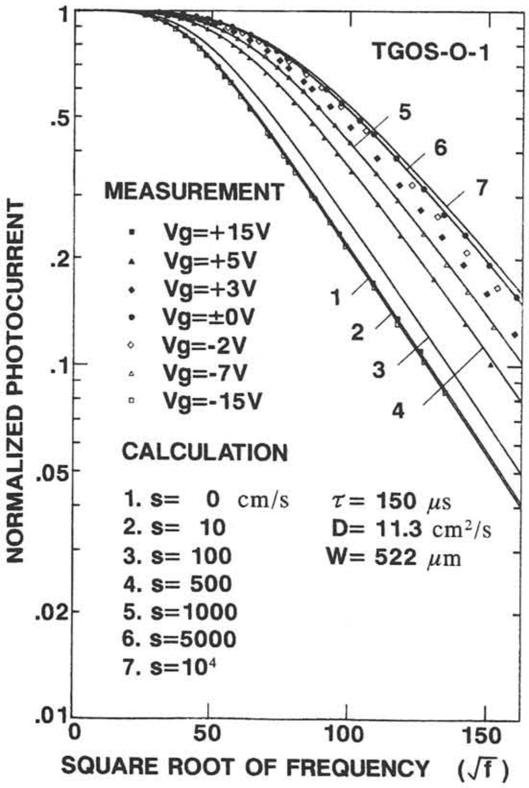

Fig. 2 Dependence of the surface recombination velocity S on gate bias voltage at the Si-SiO$_2$ interface annealed in O$_2$ at 800℃ for 30min after the dry O$_2$ oxidation. The gates were transparent ITO films.

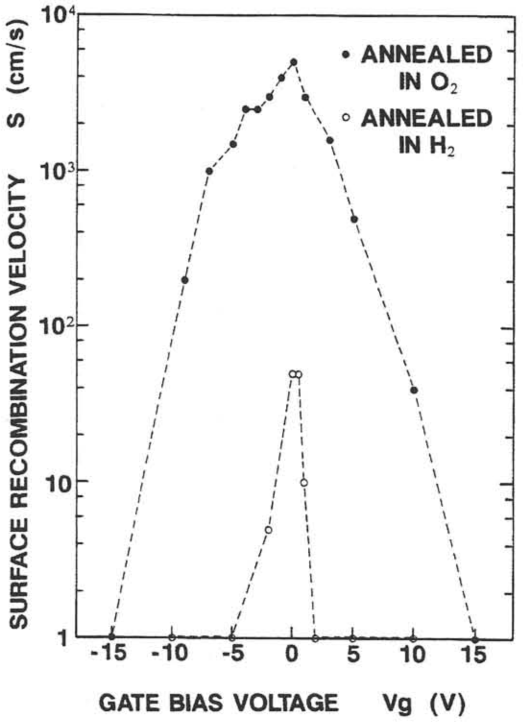

Fig. 3 Dependence of the surface recombination velocity S on gate bias voltage at the Si-SiO$_2$ interface annealed in O$_2$ at 800℃ for 30 min after the dry O$_2$ oxidation (●), and the Si-SiO$_2$ interface annealed in H$_2$ at 400℃ for 30 min after the dry O$_2$ oxidation and the ITO evaporation (○). The limit of the determination of S is about 1 cm/s.

3. Experimental results and discussions

Figure 2 shows the experimental results of the log(normalized photocurrent) vs. square root of frequency ($\sqrt{f}$) characteristics for the Si-SiO$_2$ sample annealed in O$_2$. For the calculation shown by solid curves in Fig. 2, the experimentally evaluated τ of 150 μs, D of 11.3cm^2/s, and W of 522μm were used. The dependence of the surface recombination velocity S on gate bias voltage was then determined and is plotted in Fig. 3 for both samples. For the O$_2$-annealed sample, it is obvious from Figs. 2 and 3 that the S of photo-generated minority carriers is less effective under both accumulation and inversion conditions due to lack of either majority or minority carriers at the Si-SiO$_2$ interface, which is in good agreement with the theoretical works3),4),8). This experimental result means that strong band bending at the semiconductor surface is quite effective to reduce the carrier recombination whether high D_{it} exists or not, and is suggestive for realization of a high efficiency solar cell. The broad peak of S for the sample annealed in O$_2$ may be due to a high level injection condition. Under moderate band vending or flatband condition, the S depends on D_{it} and capture cross sections, σ_p and σ_n of the interface states. The D_{it} determined by the quasi-static (sweep rate:0.02V/s) and high-frequency (100kHz) C-V measurement are plotted in Fig. 4, which indicates nearly constant and high level value within the measurement for the O$_2$-annealed sample. At near midgap region, a high level injection condition of $n_s = p_s \gg n_i$ was fulfilled. In that case, the experimentally obtainable S is

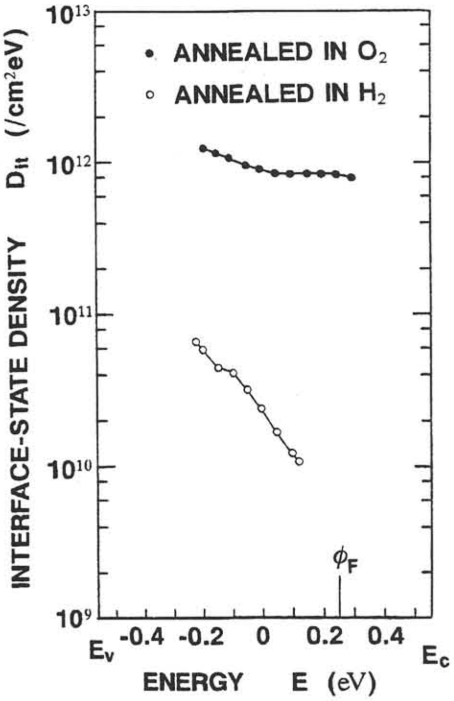

Fig. 4 Interface-state density D_{it} as a function of energy for the O_2-annealed sample (●), and the H_2-annealed sample (○). D_{it} was determined by the quasi-static and high frequency C-V measurement.

expressed as $v_{th}\{\sigma_p\sigma_n/(\sigma_p+\sigma_n)\}$(integral of D_{it} with energy), where v_{th} is the average thermal velocity of carriers. By using this relation and the experimental data for the O_2-annealed sample in Figs. 3 and 4, the smaller capture cross section is estimated to be $5\text{-}7\times10^{-16}$ cm². It has been reported that σ_p is smaller than σ_n 3). Therefore the obtained capture cross section is considered for holes. However the data for the O_2-annealed sample in Fig. 3 show the high value of S even near flatband condition, which means whether σ_p still has the order of 10^{-16} cm² in upper bandgap and/or σ_n takes the order of 10^{-16} cm². It must be said, therefore, that more works for various samples are necessary. For the H_2-annealed sample, the peak value of S is suppressed less than 50 cm/s as experimentally shown in Fig. 3. This satisfactorily corresponds to the fact that the D_{it} indicates 1.5-2 order less than for the O_2-annealed sample as shown in Fig. 4. The situation of the quite low S under accumulation and inversion condition is the same as for the sample annealed in O_2. It is apparent that a well-prepared Si-SiO_2 interface is also effective to reduce the surface carrier recombination.

4. Conclusion

The novel measurement technique of the surface recombination velocity S at the Si-SiO_2 interface based on the dual-mercury probe method has been proposed. The S for the Si-SiO_2 interfaces with different D_{it} has successfully been evaluated as a function of gate bias voltage. For each sample, the quite low S under accumulation and inversion condition and the D_{it}-dependent pyramid-like peak of S from midgap to flatband condition have been observed. The information obtainable by the proposed technique is quite useful for many minority-carrier devices, especially for solar cell design.

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