Microwave Absorption by Light-induced Free Carriers in Silicon

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Abstract.

Microwave absorption caused by free carrier was investigated using an equipment of the 9.35-GHz-microwave interferometer and a numerical analysis program. Free carrier absorption caused by light-induced carriers was investigated for silicon samples coated with 100-nm-thermally grown SiO_2 layers as well as SiO_x layers deposited by the evaporation method. The effective minority carrier lifetime and the recombination velocity at SiO_2/Si were analyzed in the case of photo-induced carrier generation with 532-nm-light illumination. The effective minority carrier lifetime was increased from 360 to 540 μs and the recombination velocity was decreased from 78 to 30 cm/s by $1.3x10^6$-Pa-H_2O vapor heat treatment at 260^oC for 3h for light illumination at 0.315 mW/cm^2 in the case of thermally grown SiO_2/Si because of passivation of SiO_2/Si interfaces. They were markedly increased from 30 to 380 μs and from 1300 to 60 cm/s by the H_2O vapor heat treatment in the case of vacuum evaporated SiO_2/Si, respectively. Light-induced free carrier absorption was also observed for sample of a pn junction formed by boron doping at a surface region by ion implantation followed by laser irradiation with no passivation layers.

Introduction

Non-destructive and non-contact measurement method of electrical properties of semiconductor is attractive as monitoring samples during the device fabrication process. Free carrier optical absorption effect is sensitive in microwave region. Free carriers in semiconductors respond to the incident electrical field of microwave on the order of GHz and complex refractive indexes can change so that transmissivity changes with the density of free carriers [1,2]. Analysis of photo-induced carrier properties is also important for photovoltaic devices such as solar cells. Measurements of microwave photoconductive decay [3] and quasi-steady-state photoconductance [4] have been widely used for measurement of the photo induced minority carrier lifetime.

In this paper, we report a precise analysis of photo-induced carrier properties in silicon using the microwave free carrier absorption effect. We present an equipment of microwave interferometer developed for sensitive detection of free carrier absorption. The density of photo induced carrier in silicon caused by light illumination is reported. We discuss changes in the effective minority carrier lifetime induced by surface passivation by high pressure H_2O vapor heat treatment. Moreover, we also report light-induced free carrier absorption for sample of a pn junction formed by boron doping at a surface region.

Experimental

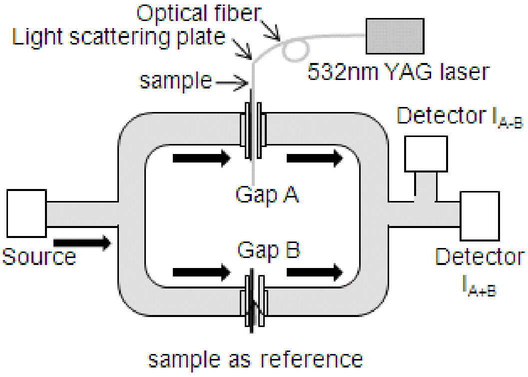

Fig.1 Schematic equipment of microwave free carrier absorption measurement system

Equipment: Figure 1 shows a schematic equipment of the free carrier absorption measurement system [5]. The 9.35-GHz microwave was emitted by a field-effect-transistor-(FET)-type oscillator. Its intensity was modulated at a frequency of 1 kHz. The microwave was introduced using a waveguide tube. It was symmetrically split into two branches by a T-type waveguide. There was a 1-mm gap each branch for measurement of sample wafers, which were inserted in the gaps A and B, respectively. The microwaves transmitted through the samples were combined using another T-type waveguide, as shown in Fig.1. The intensities of the sum I_{A+B} and difference I_{A-B} of the microwaves in the two branches were detected by high-speed-diode rectifiers and the signals were amplified by 1-kHz-lock-in amplifiers. The transmissivity of the sample A is obtained as,

$$T_A = \frac{|E_A|^2}{|E_{B0}|^2} = 2\frac{I_{A+B} + I_{A-B}}{I_0} - 1 \qquad (1),$$

where I_0 is a value of T_{A+B} when there were no samples in the two gaps. The detection accuracy of the present system in the transmissivity was ±0.1%. A thin light scattering plate was inserted into the gap A facing to the samples as shown in Fig. 1. A laser light at 532 nm was introduced using optical fibers to the light scattering plate, which gave uniform illumination of the green light to the samples. The intensity of the laser light was controlled from 0 to 3.27 mW/cm^2 at the sample surface.

Sample fabrication: In order to investigate surface effect on photo-induced carriers, four kinds of samples were fabricated using p-type silicon wafers with resistivity ranging 22~23.5 Ωcm and a thickness of 625 μm. The surfaces of every silicon wafer were coated with 100-nm-thick SiO_2 layers by the thermally grown method at 1100^{o}C at first. The silicon wafer coated with as-thermally grown SiO_2 layers was used at the gap B as reference. The same kind of silicon wafer coated with thermally grown SiO_2 layers was also inserted in the gap A and illuminated with 532-nm-green-laser light for photo-induced carrier measurement (sample 1). Heat treatment in 1.3x10^6 Pa H_2O vapor at 260^{o}C for 3h was also applied to the samples to reduce the density of defect states localized at SiO_2/Si interface (sample 2) [6]. In order to investigate low temperature surface passivation, SiO_x films were also deposited at room temperature on the top silicon surface by the vacuum evaporation of powdered SiO at a base pressure of 4x10^{-4} Pa after removing the thermally grown SiO_2 layer by buffered HF solution at the top surface and still keeping the thermally grown SiO_2 at the rear surface (sample 3). Heat treatment in 1.3x10^6 Pa H_2O vapor at 260^{o}C for 3h was also applied to the samples (sample 4). The optical reflectivity at 532 nm was measured at the surface of samples.

A sample with a pn junction was fabricated in n-type silicon wafers with a resistivity of 70 Ωcm. Boron atoms were implanted with a density of 3x10^{13}cm^{-2} and at 30 keV. They were activated by pulsed UV laser irradiation at 0.6 J/cm^2. No surface passivation with oxide layers was formed on the silicon surfaces

Theory

The free carrier absorption effect is basically explained by the Drude theory [1,2]. Free carriers in silicon vibrate according to the electrical field of the microwave. The vibration of free carriers causes a polarization, which induces change in the effective dielectric constant. The effect of photo-induced carriers caused by illumination of green light was analyzed. The complex dielectric constants are given as,

$$\varepsilon_r = \varepsilon_{Si}\left(1 - \frac{{\omega_{p1}}^2{\tau_1}^2}{1+\omega^2{\tau_1}^2} - \frac{{\omega_{p2}}^2{\tau_2}^2}{1+\omega^2{\tau_2}^2}\right) \quad (2),$$

$$\varepsilon_i = \varepsilon_{Si}\left(\frac{{\omega_{p1}}^2\tau_1}{\omega\left(1+\omega^2{\tau_1}^2\right)} + \frac{{\omega_{p2}}^2\tau_2}{\omega\left(1+\omega^2{\tau_2}^2\right)}\right) \quad (3),$$

where τ_1 and τ_2 are the lifetimes of the majority carriers and minority carriers, respectively, which are supposed to be given by the hole and electron carrier mobilities at the substrate doping concentration, $\varepsilon_{\mathrm{si}}$ is the dielectric constant of intrinsic silicon, ω_{p1} and ω_{p2} are the plasma angular frequencies of the majority carriers and minority carriers, respectively, and ε_{r} and ε_{i} is real part of the complex dielectric constant and the imaginary part of that of silicon, respectively. ω_{p1} was $7\mathrm{x}10^{11}$ rad/s in the present p-type silicon. It is much higher than the microwave frequency. For crystalline silicon, the resistivity gives the carrier density and the carrier mobility, because the relation between the carrier density and the carrier mobility has been well defined [7] and the carrier life time is given by the carrier mobility.

Light illumination with an intensity of W per unit area gives a photon flux $G=W/h\nu$ per unit area, where h is the plank constant and ν is the frequency of the green laser light. When the density of photo-induced carrier caused by photon flux G is enough lower than the density of the majority carriers par unit area, the photo-induced carrier density in-depth distribution $N_{\mathrm{photo}}(\mathrm{x})$ is given by carrier diffusion model for a steady state condition as,[8]

$$D\frac{d^2N_{photo}(x)}{dx^2} - \frac{N_{photo}(x)}{\tau_b} = 0 \quad (4),$$

where D is the electron carrier diffusion coefficient, τ_{b} is the minority bulk carrier lifetime, which is far different from the carrier lifetime τ_1 and τ_2 previously shown in eqs. (2) and (3). Although τ_1 and τ_2 typically ranging from 0.07 to 0.2 ps, the minority carrier bulk lifetime is much longer because it is the time constant of carrier annihilation. The present silicon wafers with the carrier concentration ranging from $6.0\mathrm{x}10^{14}$~ $5.5\mathrm{x}10^{14}$ cm^{-3} typically have an electron minority carrier bulk life time of about 1 ms based on a precious literature.[9] Laser light at 532nm illuminated at the top surface is absorbed within the top 1μm depth because of the high absorption coefficient of about 10^4 cm^{-1}. We therefore place the boundary condition of carrier generation and carrier recombination ratios as,

$$D\left.\frac{dN_{photo}}{dx}\right|_{x=0} = S_1N_{photo}(0) - \eta(1-r)G \quad (5),$$

$$D\left.\frac{dN_{photo}}{dx}\right|_{x=d} = -S_2N_{photo}(d) \quad (6),$$

where S_1 and S_2 are recombination velocities of the two surfaces of silicon, η is the quantum efficiency for photo carrier generation, which is assumed as 1 in this investigation, r is the optical reflectivity of sample surfaces at green laser light, d is the thickness of the silicon wafer, The eqs. (4)~(6) give the density of photo carrier $N_{\mathrm{photo}}(\mathrm{x})$ as,

$$N_{photo}(x) = \frac{\eta(1-r)G}{\left(\sqrt{\frac{D}{\tau_b}}-S_2\right)\left(\sqrt{\frac{D}{\tau_b}}+S_1\right) - \left(\sqrt{\frac{D}{\tau_b}}-S_1\right)\left(\sqrt{\frac{D}{\tau_b}}+S_2\right)e^{-\frac{2d}{\sqrt{D\tau_b}}}}\left(\left(\sqrt{\frac{D}{\tau_b}}-S_2\right)e^{-\frac{x}{\sqrt{D\tau_b}}} + \left(\sqrt{\frac{D}{\tau_b}}+S_2\right)e^{-\frac{2d-x}{\sqrt{D\tau_b}}}\right) \quad (7).$$

The total photo induced minority carrier density per unit area n is obtained by integration of $N_{\mathrm{photo}}(\mathrm{x})$ from 0 to d as,

$$n = \frac{\eta(1-r)G\sqrt{D\tau_b}\left(1-e^{-\frac{d}{\sqrt{D\tau_b}}}\right)}{\left(\sqrt{\frac{D}{\tau_b}}-S_2\right)\left(\sqrt{\frac{D}{\tau_b}}+S_1\right)-\left(\sqrt{\frac{D}{\tau_b}}-S_1\right)\left(\sqrt{\frac{D}{\tau_b}}+S_2\right)e^{-\frac{2d}{\sqrt{D\tau_b}}}}\left(\sqrt{\frac{D}{\tau_b}}-S_2+\left(\sqrt{\frac{D}{\tau_b}}+S_2\right)e^{-\frac{d}{\sqrt{D\tau_b}}}\right) \qquad (8).$$

In the present case, the electron minority carrier diffusion coefficient D is 36 cm^2/Vs. We also assume that the both surfaces coated with thermally grown SiO_2 have a same quality with a same minority carrier recombination velocity.

The calculation program confirmed that the detection accuracy 0.1% of the present microwave equipment allowed us to observe change in a photo carrier density per unit area of $5\text{x}10^{10}$cm^{-2}. It means that the present measurement and analysis system has a possibility of investigation of photo-induced carrier behavior in a low injection condition. The photo induced minority carrier density per unit area n gives the effective minority carrier lifetime τ_{eff} as,

$$n = \eta(1-r)G\tau_{eff} \qquad (9),$$

where carrier annihilation rates at the surfaces and in the silicon bulk are reciprocally represented by τ_{eff}, which corresponds to the effective minority carrier lifetime obtained by conventional equipments [3,4]. When τ_{b} is given, S_1 and S_2 as well as $N_{\mathrm{photo}}(\mathrm{x})$ can be analyzed using eqs (7) and (8).

Results and discussion

Transmissivity of 9.35-GHz-microwave is determined by the optical interference effect caused by spatially distribution of Fresnel coefficient. Figure 2 shows transmissivity of silicon wafers with different resistivity as a function of substrate thickness. The transmissivity changed periodically with the substrate thickness in the case of 10000 Ωcm because of change in phases between microwaves incident at the top and reflected from the rear surfaces. The transmissivity decreased as the resisistivity decreased because free carrier optical absorption became important. There was a substantial absorption for the sample with a thickness of 625 µm at 23 Ωcm and the transmissivity was 27%.

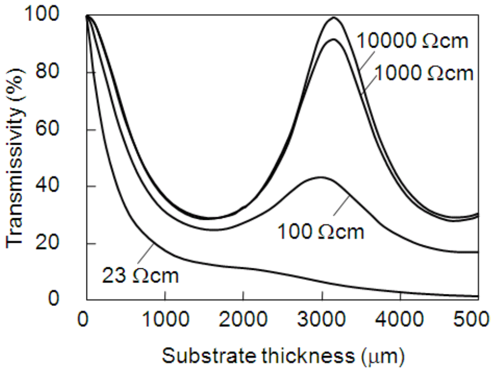

Fig.2: Transmissivity of silicon wafers with different resistivities as a function of substrate thickness.

Figure 3 shows the transmissivity as a function of the intensity of 532-nm light illumination for four kinds of silicon samples. Solid triangles show transmissivity for the sample with both surfaces coated with thermally grown SiO_2 layers. Open triangles show transmissivity after high-pressure H_2O vapor annealing of the sample with both surfaces coated with thermally grown SiO_2 layers. Solid circles show transmissivity for the sample with the top surface coated with SiO_x layers. Open circles show transmissivity after high-pressure H_2O vapor annealing of the sample with the top surface coated with SiO_x layers. The transmissivity monotonously decreased as the light intensity increased from 0 (dark field) to 3.27 mW/cm^2 for every sample. This is because of free carrier absorption by photo-induced

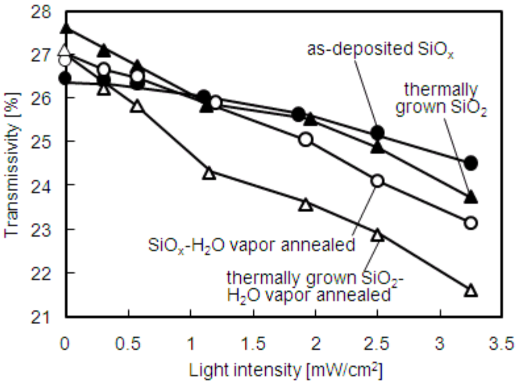

Fig.3: Transmissivity as a function of the intensity of 532-nm light illumination for four kinds of silicon samples.

carriers. The sample with the both surfaces coated with thermally grown SiO_2 and high-pressure H_2O vapor annealed showed the highest decrease in transmissivity from 27.1 to 21.6% as the light intensity increased from 0 to 3.27 mW/cm^2. On the other hand the sample with as-deposited SiO_x layer on the top surface showed the lowest decrease in transmissivity from 26.5 to 24.5%.

Figure 4 shows the effective minority carrier lifetime (a) obtained by the results of Fig.3 and the surface recombination velocity (b) when the electron minority carrier bulk lifetime was assumed to be 1 ms. The sample treated with high-pressure H_2O vapor annealing of silicon with the both surfaces coated with thermally grown SiO_2 had highest effective minority carrier lifetimes ranging from 400 to 540 µs for the light intensity ranging from 0.315 to 3.27 mW/cm^2. On the other hand, the sample with the both surfaces coated with thermally grown SiO_2 before high-pressure H_2O vapor annealing had an effective minority carrier lifetime ranging from 260 to 360 µs. High-pressure H_2O vapor heat treatment increased the effective minority carrier lifetime because of passivation of thermally grown SiO_2/Si interfaces. The sample as-deposited SiO_x layer on the top surface had low effective minority carrier lifetimes, which markedly increased from 30 to 180 µs as the light intensity increased from 0.315 to 3.27 mW/cm^2. It indicates that as-deposited SiO_x/Si interface had substantial defect states which reduced the effective minority carrier lifetime. The effective minority carrier lifetime was increased by high-pressure H_2O vapor annealing to 250 to 380 µs similar to that of sample coated with thermally grown SiO_2 layers. This indicates that high-pressure H_2O vapor heat treatment effectively passivated SiO_x/Si interfaces.

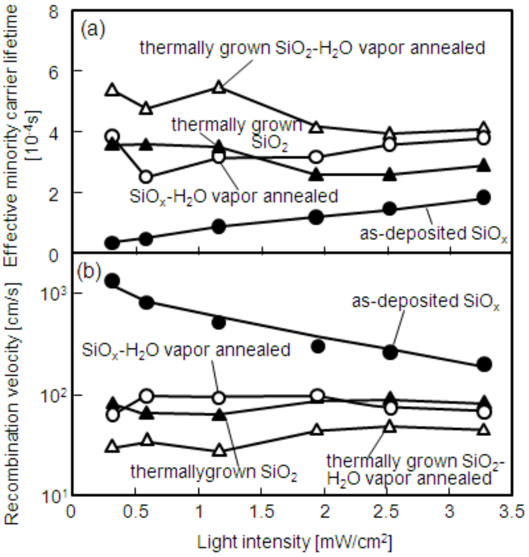

Fig.4: Effective minority carrier lifetime (a) and recombination velocity (b) as a function of the intensity of 532-nm light illumination.

The sample treated with high-pressure H_2O vapor annealing of silicon with the both surfaces coated with thermally grown SiO_2 had the lowest recombination velocity ranging from 25 to 45 cm/s, which was almost constant for the light intensity ranging from 0.315 to 3.27 mW/cm^2. On the other hand, the sample with the both surfaces coated with thermally grown SiO_2 had the recombination velocity ranging from 65 to 90 cm/s. High-pressure H_2O vapor heat treatment achieved passivation of thermally grown SiO_2/Si interfaces by reduction of the recombination velocity. The sample as-deposited SiO_x layer on the top surface had a high recombination velocity, which markedly decreased from 1300 to 200 cm/s as the light intensity increased from 0.315 to 3.27 mW/cm^2. It indicates that as-deposited SiO_x/Si interface had substantial defect states which caused serious recombination of photo-induced carriers. The recombination velocity was decreased by high-pressure H_2O vapor annealing to 60~90 cm/s similar to that of sample coated with thermally grown SiO_2 layers.

Figure 5 shows the transmissivity as a function of the intensity of 532-nm light illumination for boron doped samples. The transmissivity decreased from 36.4 to 35.3% as the light intensity increased from 0 to 3.27 mW/cm^2 when the laser light was irradiated to the boron doped top surface. The density of photo-induced carrier increased to 4.0x10^{11} cm^{-2}. However no change in transmissivity was observed when the laser light was irradiated to the rare surface. Dashed lines are a calculated transmissivity when the recombination velocities were 0 cm/s for the boron doped surface and 30000 cm/s for the rear surface. Good agreement between experimental and calculated transmissivities means that the pn junction decreased the recombination velocity because of formation of potential barrier. Heavily boron doped regions decreased electron density at the top surface and decreased recombination probability.

5. Summary

We reported free carrier absorption in order to analyze electrical properties of silicon. A 9.35-GHz microwave interferometer was constructed by waveguide tubes with having two narrow gaps for measurements of silicon wafers. We also developed a numerical analysis program including free carrier optical absorption and the optical interference effect in order to calculate the microwave transmissivity. Free carrier photo absorption caused by photo-induced carriers was experimentally measured and numerically analyzed for 625-µm-thick silicon samples coated with 100-nm-thermally grown SiO_2 as well as SiO_x layers deposited on the top-surface by the evaporation method. The 532-nm light illumination ranging 0.315 to 3.27 mW/cm^2 decreased the transmissivity owing to free carrier absorption caused by photo-induced free carriers. The present equipment detected photo-induced minority carrier density per unit area above 5x10^{10}cm^{-2}. The effective minority carrier lifetime was analyzed. It increased from 360 to 540 cm/s for illumination at 0.315 mW/cm^2 by 1.3x10^6-Pa-H_2O vapor heat treatment at 260°C for 3h in the case of thermally grown SiO_2/Si because of passivation of SiO_2/Si interfaces. It markedly increased from 30 to 380 µs by the H_2O vapor heat treatment in the case of SiO_x layers deposited at the top surface. The recombination velocity was analyzed when the minority carrier bulk lifetime was assumed to be 1 ms. It was decreased from 78 to 30 cm/s for illumination at 0.315 mW/cm^2 by 1.3x10^6-Pa-H_2O vapor heat treatment at 260°C for 3h in the case of thermally grown SiO_2/Si because of passivation of SiO_2/Si interfaces. It was markedly decreased from 1300 to 60 cm/s by the H_2O vapor heat treatment in the case of SiO_x layers deposited at the top surface. Formation of pn junction by 3x10^{13}-cm^{-2}-boron doping in a 70-Ωcm-n-type silicon reduced the surface recombination velocity and caused a density of photo-induced carrier of 4.0x10^{11} cm^{-2} at 3.27 mW/cm^2 light illumination.

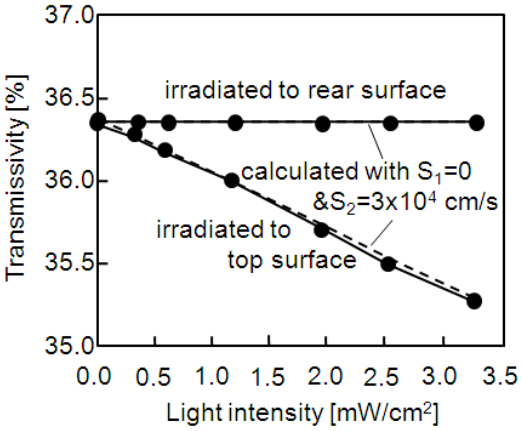

Fig.5 Transmissivity as a function of the intensity of 532-nm light illumination for boron doped samples. Dashed lines are a calculated transmissivity when the recombination velocity is 0 cm/s at the boron doped surface and 30000 cm/s at the rear surface.

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