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Photothermal microscopy of silicon epitaxial layer on silicon substrate with depletion region at the interface

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Photothermal microscopy has been used for investigating semiconductor materials to evaluate carrier diffusivity, lifetime, and surface recombination velocity. The effects of the depletion region between epitaxial and substrate Si with different conduction types are studied. Although the observed curves are well explained by the theoretical predictions for surface reflectivity, no drastic change is observed for the different structures. This may be due to the fact that the thickness of the epitaxial layer is too large to reveal clearly the effect of the depletion region at the *PN* junction. However, the result for low-frequency modulation at 10 kHz may indicate this effect. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1515893]

I. INTRODUCTION

Modulated photoreflectance is a noncontact and nondestructive characterization technique of semiconductors. Photothermal microscopy has been used for investigating semiconductor materials to evaluate carrier diffusivity, lifetime, and surface recombination velocity.[1] Surface change induced by an ion implantation had been well characterized by this technique.[2]

Recent technological developments for Si epitaxial layers provide for increased reliability of semiconductor devices and ultimately more functional integrated circuit devices. Therefore, it becomes important to characterize both the epitaxial layer itself and the interface between the epitaxial layer and substrate in more detail. In this article, we report on the results of photothermal microscopy measurements for epitaxial Si layers on substrates with different conduction types and investigate the effect of interface electric field on the carrier diffusion mechanism.

II. PRINCIPLES OF THE PHOTOTHERMAL MICROSCOPY

When a laser light is illuminated on the sample surface, photoexcited free carriers diffuse along and parallel to the direction of the sample thickness and recombine in the bulk and at the surface. The carrier concentration $n(r,t)$ in the sample is determined by solving the carrier diffusion equation, with appropriate boundary conditions at the surface, as

$$\frac{\partial n}{\partial t}=D\nabla^2 n-\frac{n}{\tau}+\Phi, \tag{1}$$

where D, τ, and Φ are electron diffusivity, carrier lifetime, and incident photon flux, respectively. Surface recombination velocities are taken into account for the boundary conditions, and the quantum efficiency is supposed to be 1, for simplicity. Temperature rise $T(r,t)$ in the sample under light illumination at photon energy $h\nu$ larger than that of band gap energy E_g is calculated by solving the thermal diffusion equation given below:

$$\frac{\partial T}{\partial t}=D_T\nabla^2 T+\frac{h\nu-E_g}{\rho C}\Phi+\frac{E_g}{\rho C}\frac{n}{\tau}, \tag{2}$$

where D_T, ρ, and C are thermal diffusivity, density, and specific heat, respectively. The heat source for Eq. (2) arises from the following two mechanisms. First, it is due to fast carrier nonradiative relaxation to the conduction-band minimum or valence-band maximum. The energy of $(h\nu$-$E_g)$ is dissipated in this case [second term of Eq. (2)]. Second, it is the nonradiative recombination of free carriers diffused throughout the sample with energy E_g (third term).

Photothermal microscopy detects the change of the surface reflectivity by the modulated light illumination. The relative reflectivity change at the surface is, then, calculated by

$$\frac{\Delta R}{R}=\frac{1}{R}\frac{\partial R}{\partial T}\Delta T+\frac{1}{R}\frac{\partial R}{\partial n}\Delta n. \tag{3}$$

Since Eqs. (1) and (2) determine the distribution of photogenerated carriers and the temperature rise at the illuminated surface, the expected relative reflectivity is calculated.

III. EXPERIMENT

Temperature rise due to photoexcitation by an Ar^+ ion laser of 514 nm as a pump beam was measured in terms of a reflectivity change on the sample surface. The reflectivity was measured by a probing laser diode of 670 nm. Both laser beams are focused through the microscope in a micron scale and a dichroic mirror is used to change the distance between

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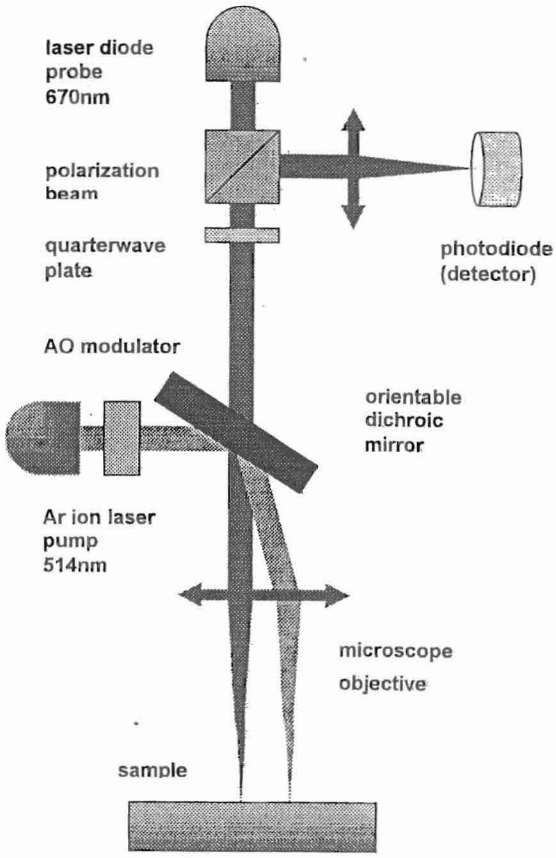

FIG. 1. Schematic illustration of the photothermal microscope.

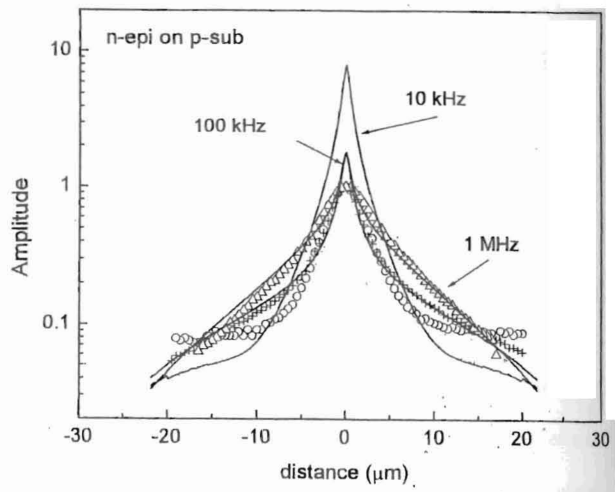

FIG. 2. Photoinduced modulated reflectivity amplitude of Si n/P sample as a function of pump–probe distance.

the pump and probe laser beam.[3] The experimental setup for this technique is schematically shown in Fig. 1. Measurements were carried out at room temperature on four silicon epitaxial samples grown by Komatsu Electronic Metal, Co., Ltd. They were n-type epitaxial layers on p- and n-type substrates (refer to n/P and n/N, respectively), and vice versa. The physical parameters for the sample are listed in Table I. The modulation frequencies were set at 10, 50, 100, and 500 kHz, and 1 MHz. The light illuminated on the epitaxial layer side of the sample and the reflected beam was also detected from the same side.

IV. RESULTS AND DISCUSSION

The typical photoinduced reflection amplitude and phase of the n/P sample are shown in Figs. 2 and 3, respectively. Horizontal axes are taken for the distances from the pump and probe laser beam. The results show that the thermal contribution becomes large when the modulation frequency decreases. Since it is known that factors $\partial R/\partial T$ and $\partial R/\partial n$ are of opposite signs for Si samples, the contribution of the two terms on the right-hand side of Eq. (3) is easily distinguished.[3,4] The phase shift of 180° is expected.

Theoretical calculations were carried out to obtain the photoreflection phase and amplitude signal as a function of pump–probe distance by using Eq. (3).[3] Best-fitted curves for the experimental results are drawn in the figures by the solid curves in Figs. 2 and 3. Although we could not obtain complete fitting for $f = 10\,\text{kHz}$, good agreement might be concluded. The observed parameters are 18 cm^2/s and 3000 cm/s for electron diffusivity and surface recombination velocity at the illuminated surface, respectively. The rear-side recombination velocity did not affect the shape of the curves. This may be due to the fact that carriers could not reach the rear surface. A carrier lifetime and a ratio $(\partial R/\partial n)/(\partial R/\partial T)$ was estimated as 50 μs and 5.0×10^{-22}, respectively. The observed parameters are in the same order as reported.[1]

Similar measurements were also carried out for other samples with different structures, as shown in Table I. Figure 4 shows the results of the reflection phase for the p/N sample. No drastic change was observed except for the curve at 10 kHz. The phase becomes flatter than that of Fig. 3 for the distance above 5 μm and below -5 μm. These results suggest a larger electron diffusivity or a larger surface recombination velocity for the p/N samples. The phase spectra for n/N and p/P are also measured. No significant difference were observed. Thermal and electron diffusion length are around 54 ($D_T = 0.9\,\text{cm}^2/\text{s}$) and 230 μm ($D = 18\,\text{cm}^2/\text{s}$) at 10 Hz, which is smaller and larger, respectively, than the epitaxial layer thickness of 75 μm in the present experimental conditions. Therefore, the generated heat at the p–n junction interface cannot reach the surface for higher modulation

TABLE I. Silicon epitaxial layer samples grown on Si substrates.

	Si epitaxial layer			Si substrate		
No.	type	$\rho(\Omega\,\text{cm})$	L (μm)	type	$\rho(\Omega\,\text{cm})$	L (μm)
p/N	p	4.4	78	n	4.3	350
p/P	p	4.4	78	p	3.7	350
n/N	n	5.1	78	n	4.3	350
n/P	n	5.1	78	p	3.7	350

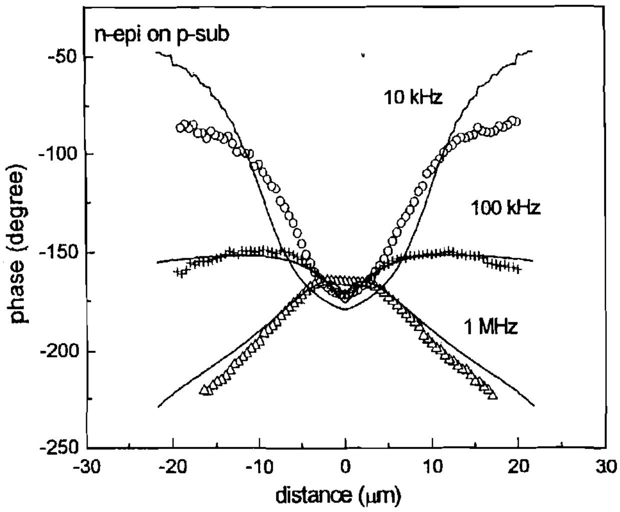

FIG. 3. Photoinduced modulated reflectivity phase of Si n/P sample.

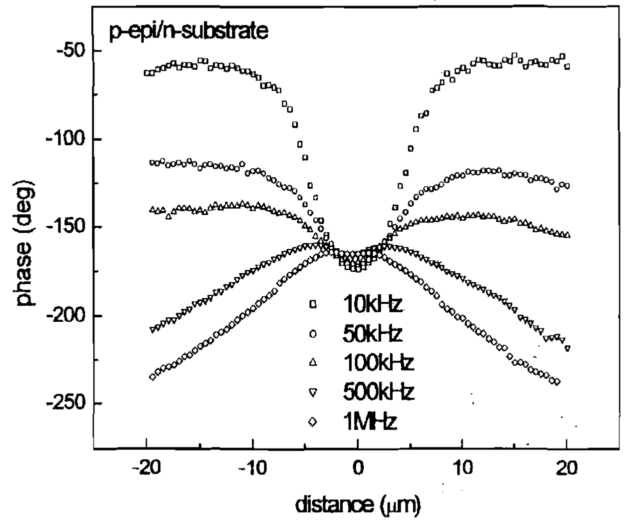

FIG. 4. Photoinduced modulated reflectivity phase of Si p/N sample.

frequencies of 100 kHz and 1 MHz, even when the photogenerated carriers can reach the depletion region. This does not contribute to the present photoreflection signal. This may be the reason that no drastic effects were observed for samples with different structures. However, the deviation of the experimental data from the theoretical one at 10 kHz may lead to considering the possibility of a contribution from the depletion region. In this case, part of the heat may reach the surface. Since the carrier diffusion is limited by ambipolari diffusion, changes of the electron and hole concentrations drastically affect the diffusivity near the depletion region. The electric field in the depletion region drifts the carriers. The carrier lifetime is also influenced by the electric field. Although some propositions may explain the deviation at 10 kHz, the detailed mechanism is complicated. Thinner thicknesses for the epitaxial layer are necessary to discuss the effect of the electric field (carrier drift) and the PN junction depletion region.

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