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Ultrafast carrier dynamics in highly implanted and annealed polycrystalline silicon films

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Abstract. We have studied the ultrafast optical response of highly implanted and annealed polycrystalline silicon films. One-micron thin polycrystalline silicon samples-on-quartz implanted with As ions at a high dose of 2x10¹⁶ cm⁻² at 100keV and annealed at various temperatures have been investigated using ultrafast pulses. Frequency doubled amplified femtosecond pulses at 400nm have been used in a pump-probe configuration to measure the temporal reflective response from the polysilicon samples. A super-continuum of ultrafast laser pulses were generated and used in probing the samples at various wavelengths in the visible part of the spectrum. Transient reflection measurements reveal negative and positive contributions to the change in the index of refraction of the samples attributed to an increase in the carrier density and lattice temperature. Ion induced defects and subsequent annealing are key contributing factors in the dynamic behavior of these samples.

1. Introduction

Femtosecond carrier dynamics in semiconductors has been investigated using excitation-probe techniques over the past two decades [1]. Even though, there has been a great deal of investigating work in this area, the continuous miniaturization of semiconductor devices into the nano-scale regime and the complexity of the devices themselves have emphasized the importance of understanding the carrier dynamics on increasingly shorter time scales and over a large span of energy excitations. Clearly, the understanding of semiconductor processing such as ion implantation and subsequent annealing on the carrier dynamics is of critical importance in the microelectronics industry. The recent demand for high-speed micro-electronic devices with ultrafast response has given a renewed interest in this area. Although crystalline silicon has a slow response, it is known that amorphous silicon [2,3] and amorphization due to ion implantation process [4] alter the temporal behavior in these materials. Amorphous silicon has been reported with an ultrafast response shorter than picosecond due to the short free-carrier lifetime. The reduction of the free carrier lifetime is the result of the introduction of defects into the crystalline semiconductor, which act as traps and recombination centers [5]. It is well known that above bandgap, direct or indirect optical excitation of semiconductors generates electrons and holes. Following optical excitation, electrons and holes undergo spatial and temporal evolution with characteristic times, which depend on the various relaxation processes [1].

Here we report on ultrafast transient reflectivity measurements using highly implanted polycrystalline silicon and annealed at various temperatures. The technique utilizes a pump pulse to excite carriers, which are monitored using a super-continuum generated weaker probe beam, through
the changes induced in the index of refraction of the material. The variation in the index of refraction is monitored as change in the reflectivity, which is a direct measure of the photo-excited carrier lifetime, and in fact, a measure of the recombination traps in the polycrystalline silicon.

2. Experiment

Time-resolved measurements of the carrier dynamics were carried out using a femtosecond pump-probe technique, in which a short pump pulse excited carriers in the sample and a time delayed probe pulse measured the resulting changes in reflection as a function of the pump-probe optical delay. The experimental setup is shown in figure 1.

![Experimental setup for ultrafast transient reflectivity measurements. The excitation pulses at 400nm were generated using a BBO crystal and the probe pulses were generated using white light super continuum from a water cell.](image)

The laser pulses were generated using an amplified Ti: Sapphire laser system (Spectra-Physics) operating with a repetition rate of 1kHz and centered at 800nm. The experimental arrangement was used to separate the incident laser beam into a pump and probe beam. The fundamental 100fs pump beam was then frequency doubled using a BBO non-linear crystal providing 400nm excitation pulses for the experiments. A small portion of the fundamental beam was used to generate white light continuum (450 -750nm) and this was utilized as the probe beam in the experiments. The pump beam was set approximately to 10μJ/pulse and was weakly focused to 2 mm diameter spot size. The white light probe was focused to 100μm diameter spot size within the 400nm pump beam. The relative angle of incidence to the sample of the two beams was less than 10°. A set of narrow bandpass filters in front of a silicon photodiode was used to select the probing wavelength of the reflected white light beam. The signal was processed with a lock-in amplifier. Under the excitation condition of the experiment no apparent damage was induced on the samples.

The samples used in these experiments are 1μm polycrystalline silicon films on quartz implanted with arsenic ions at doses of 2x10^{16} ions/cm² and implantation energy, E=100keV through a thin oxide layer at room temperature. After implantation the thin oxide layer was removed and samples were then thermally annealed isochronically at various temperatures up to 1100°C for 1 hour in an inert nitrogen atmosphere.
3. Results and discussion

Figure 2a shows traces of the transient reflectivity changes for the non-annealed and annealed at 500°C implanted polysilicon samples. The reflectivity changes are typical for low temperature annealed samples in the probing wavelength range between 450 to 700nm. The data exhibit a fast rise followed by a slow recovery back to the equilibrium reflectivity. In figure 2b measurements are shown for the annealed samples at 700°C.

![Graph showing transient reflectivity changes](image)

**Figure 2.** (a) Transient reflectivity changes for non-annealed and annealed at 500°C implanted polycrystalline silicon films at probing wavelengths of 450nm, (b) Measurements of implanted and annealed at 700°C polysilicon films. The curves correspond to data for probing wavelengths at 450, 600 and 700nm.

Optical excitation of semiconductors with above bandgap photons generates carriers. These carriers relax through various mechanisms [1], with most of their energy transferring to the lattice. This energy transfer raises the temperature of the lattice resulting in the change of the refractive index. Therefore the observed changes in reflectivity are due to an increase in the carrier density and a rise in the lattice temperature. The initial increase in the carrier density results in a negative contribution to the reflectivity, whereas a rise in the lattice temperature causes an increase in the reflectivity. The recovery of the initial photo-generated carrier concentration within the probing region is mainly due to three factors; surface recombination, recombination due to the ion induced defects, and diffusion of the carriers into the bulk.

It is believed that the defects generated in the implanted samples (which are present in the low temperature annealed samples) act as recombination centers resulting in the fast removal of the non-equilibrium carriers followed by a strong rise in temperature. These measurements were wavelength independent since the damage induced by the implantation kept the penetration depth within the defect region. Here we should point out that a higher temporal resolution measurement revealed a negative contribution to the reflectivity (inset figure in 2a) which is typical for the probing wavelength range between 450-700nm close to t=0 due to the initial non-equilibrium photogenerated carriers with lifetime estimated to be less than 1ps. The strong wavelength dependence seen in Fig. 2b is due to the partial removal of the defects resulting in smaller number of recombination centers and longer penetration depth of the probing wavelengths. This is clearly evident at the longest probing wavelength (700nm) where the carrier lifetime is of the order of 15ps (inset figure in 2b).

Traces of transient reflectivity change for the highest annealed implanted (1100°C) poly-silicon sample at different probing wavelengths are also shown in figure 3. The absolute value of the reflectivity change was on the order of $10^{-4}$. The signal was demonstrated to behave in a linear fashion for the excitation intensities utilized in these experiments. Each response initially had a rapid decrease, followed by a recovery from negative to positive values with increasing time.
Figure 3. Transient reflectivity changes for implanted and annealed at 1100°C polycrystalline silicon films. The curves correspond to data for probing wavelengths at 450, 500, 550 and 600 nm. The inset shows the reflectivity curve at 450 nm expanded on the time scale.

It is well known that annealing at high temperatures remove defects generated from implantation [5,6]. This was also demonstrated using spectroscopic ellipsometry and photothermal techniques in these samples [7]. The temporal behavior of the recovery towards equilibrium of the negative reflectivity change seen in these samples is attributed to relaxation mechanisms other than the defect recombination. Consequently, mechanisms like surface recombination and diffusion are the contributing factors to the decay of the carriers (supported from carrier dynamic simulations [1,5]). Furthermore, we notice that the recovery time, following the decrease in the reflectivity, increases with increasing probing wavelength. This observation also indicates that mechanisms like surface recombination and diffusion of carriers are the main causes of the observed recovery of the reflectivity whose effect decreases with increasing depth from the surface of the sample.

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