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Damage annealing process in implanted poly-silicon studied by nanocalorimetry: Effects of heating rate and beam flux

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Abstract

Nanocalorimetry of ion-implanted damage annealing in polycrystalline Si is presented. Si was implanted at 30 keV. Temperature scans were performed between room temperature and 350 °C at heating rates between 48 and 144 kK/s for a fluence of 1×10^{13} Si/cm^2, and between room temperature and 540 °C at beam fluxes of 11 and 44 nA/cm^2 with a fluence of 2×10^{13} Si/cm^2. The heat release shows no features, but rather a broad increase with temperature which is characteristic of a series of processes continuously distributed in terms of activation energy. Higher heating rates shift the signal towards higher temperatures and decrease its amplitude, which is typical for thermally activated processes. Lower beam flux implants translate into smaller heat release. This is partly attributed to shorter implantation times at higher fluxes, which leave less time for dynamic annealing, but could also be due to the higher impact rate in the environment of previously generated disordered zones. Such impact generates damage that may stabilize disordered zones, which would have enough time to undergo dynamic annealing at lower fluxes.

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Keywords: Nanocalorimetry; Ion implantation; Damage annealing; Heat rate; Beam flux

1. Introduction

Semiconductor doping by ion implantation is facing many challenges as the technology evolves towards ultra-shallow junctions and transistor half-pitch well below 100 nm [1]. By generating defects in the lattice, implantation strongly influences the way dopants diffuse and are activated. It was

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evidenced that point defect go through a clustering phase before forming {3 1 1} rod-like defects around 700 °C [2]. Their coarsening is responsible for the transient enhanced diffusion [3].

Recently, our group introduced nanocalorimerty as a way to investigate from the thermal point of view the kinetics of damage annealing in silicon implanted at low energy [4,5]. This technique operates on similar principles as conventional differential scanning calorimetry (DSC), but fast heating rates (10^4–10^6 K/s) and low thermal losses make possible the observation of thermal processes in thin films or at surface, involving energies of the order of the nJ [6]. Considering the type of information it provides in terms of activation energies and amount of heat released by low energy implantation defects, nanocalorimetry can be extremely useful in elucidating the mechanisms underlying damage annealing. In implanted polycrystalline silicon (poly-Si), it was shown recently that the amount of heat released as a function of temperature has the same shape from very low to high fluences [5]. This implies that the underlying processes are the same, as if each impacting ion readily produced damage structures similar to what is found in heavily damaged Si. In this paper, we report on nanocalorimetry experiments, where the heat released by damage annealing following self-implantation of poly-Si is investigated for different heating rates and beam currents.

2. Nanocalorimetry experiments

Our nanocalorimeters consist of a low stress Si_3N_x membrane 150 nm thick on the surface of which is deposited a Pt strip (25 nm thick, 0.5 mm in width, 7.4 mm in length). This strip serves both as a heater and a thermometer, through a resistance measurement. For our implantation experiments, a 140 nm amorphous Si layer was deposited by plasma sputtering on the opposite side of the membrane, in line with the Pt heater. The membrane ensures a good thermal conduction between the sample and the heater, while it isolates them electrically. Prior to the implantations, the nanocalorimeters were annealed at 900 °C during 100 s in a N_2 atmosphere to form a poly-Si layer with crystallites of ~75 nm.

Nanocalorimetry measurements are initiated by supplying a current pulse of 8 ms to the Pt heater, thus raising the temperature of the system by Joule heating. Here, the current pulses varied from ~35 mA to ~57 mA, providing heating rates between 48 and 145 kK/s. For slower scans, subsequent higher heating rate scans were performed in order to ensure proper annealing at more than 700 °C. The current and voltage were monitored in real time during the pulse, so the heat supplied to the system ($P = VI$) was obtained. The temperature during the scan was determined using a calibration of the Pt strip resistance versus temperature established beforehand. However, the implanted nanocalorimeter overheated during the fastest scans, which came the last, causing its resistance to change by 4%. This resulted in an error of 10 °C on the temperature scale for this scanning rate. The measurements were achieved in differential mode using two nanocalorimeters placed side-by-side in the implantation chamber, one of them being implanted (imp) in order to induce damage, while the other served as reference (ref) and remain unimplanted. A detailed description of the method used to extract the heat capacity of a deposited layer, including the subtraction of baselines to account for the fact that the implanted and reference calorimeters are not identical, and to correct for thermal losses, can be found in [7],[8]. Here, poly-Si is deposited on both nanocalorimeters, so heat capacity does not nominally contribute any net signal; only damage annealing does. Any difference in heat capacity between the implanted and reference nanocalorimeters is subtracted by carrying out baseline measurements. Roughly, the heat rate, i.e. the amount of heat transferred to a process per unit degrees, is given by

$$q(T) = (VI/v)_{\mathrm{imp}} - (VI/v)_{\mathrm{ref}} \tag{1}$$

where v is the temperature scanning rate. The effect of damage annealing, by releasing heat to the implanted nanocalorimeter, is to increase slightly its heating rate. A released heat thus corresponds to a negative value of $q(T)$. The results presented here show amounts of heat released, thus $-q(T)$.