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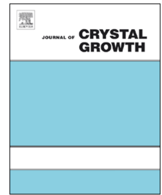

Formation of dendritic crystal structures in thin silicon films on silicon dioxide by carbon ion implantation and high intensity large area flash lamp irradiation

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ABSTRACT

In this paper, we use large area light pulse induced melting of deposited thin silicon films on oxidised silicon wafers to prepare coarse grained dendritic crystal structures. The results show that the addition of carbon prevents the agglomeration of the molten silicon films and largely influences the crystallisation process. The low solubility of carbon in liquid silicon and its effect on the silicon melting temperature induces a distinctive lateral dendritic grain growth. XTEM, SEM, AFM and ToF-SIMS investigations have been performed to study the crystallisation process and to characterise the resulting film structure.
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1. Introduction

The transformation of deposited polycrystalline or amorphous silicon layers on amorphous substrates into large grained, high quality crystalline layers is of great interest for specific microelectronic key technologies, like SOI [1] or for solar cell production [2]. However, in comparison to well-established methods, like SIMOX or wafer bonding, the lack of any lattice information from the crystalline substrate requires new approaches. Crystallisation methods, like laser annealing [3,4], or small area flash lamp annealing [5], based on short time melting processes, allow the improvement of the crystallinity of deposited layers in the hindsight. Seed Selection through Ion Channelling (SSIC) represents another possible approach to increase the grain size with the additional effect of enhanced texturizing. The first results to that were reported already in the 80s by Kung et al. [6]. However, this method requires a high technical effort and the results are very sensitive to the exact selection of the implantation parameters and the initial structure of the as-deposited film, so that it has not found broad application in industry until now.

In this paper a new SOI technique is presented based on large area flash lamp induced recrystallisation of deposited silicon layers on SiO_2 [7]. The idea behind this is to melt during the light pulse rapidly and completely the whole silicon over layer and to adjust the cooling down velocity and the layer properties insofar, that the following solidification process results in the formation of very large-grained, dendritic crystal structures.

2. Experimental details

2.1. Sample preparation

Two sets of samples (series-A and series-B) were processed as follows. Starting with 0.5 mm thick 4-inch (100) Si wafers, first a 140 nm thick silicon dioxide film was thermally grown on the surface in dry oxygen. After that, a 100 nm thick amorphous silicon film was deposited by Electron Beam Evaporation at a pressure of 5×10^{-7} mbar and a rate of 1 nm/s, without substrate heating. Series B was additionally implanted with 25 keV C^+ ions at room temperature at a fluency of $5 \times 10^{16}/cm^2$. According to

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SRIM calculations, R_p was located near 87 nm, which is slightly before the Si/SiO_2 interface, with a maximum carbon concentration of about $5 \times 10^{21}/cm^3$.

2.2. The FLA (Flash Lamp Annealing) system

After the carbon implantation (only series B) samples of both series were irradiated in argon atmosphere with large area light pulses from the FLA system. The typical parameters of the flash process were: rectangular over time pulse shape, pulse length 20 ms, maximum wafer diameter 100 mm, maximum energy density 150 J/cm^2. For more technical details, see [7]. Usually, to induce melting of the deposited layer, energy densities in the range between 110 J/cm^2 and 120 J/cm^2, and a constant preheating temperature of 700 °C were necessary. Thereby, as will be discussed in more detail in Section 3.3, the preheating time of 1 min and the relatively long pulse time of 20 ms guarantee, that the a-Si layer will be converted completely into fine grained poly-Si before the melting temperature is reached.

2.3. The strong influence of carbon admixture on the crystallisation process

Dendritic crystal growth from the melt usually results in the formation of highly extended crystal structures [8]. In the present work, using FLA, an attempt was undertaken to induce even lateral dendritic crystal growth in a rapid molten silicon layer. For that usually a high lateral temperature gradient is necessary. Such a gradient exists near the wafer edge, immediately after the flash pulse is over. On the one side the wafer edge gets additional illumination from the extended flash lamps, located at a relatively small distance above the wafer. This results in a higher temperature near the edge and, as a consequence, melting of the layer starts here. On the other side the situation changes after the light pulse is over. The following simple example calculation shows that due to the additional heat loss at the wafer edge a considerable negative axial temperature gradient is formed after the flash.

Taking into account the high temperature value for the heat diffusivity in silicon of about 0.15 cm^2/s [9] and a elapsed time of 0.1 s after the light pulse, which is sufficient to cool down a 0.5 mm thick wafer by about 70°, as estimated using the thermodynamic variables given in [10], a value for the heat diffusion length $(Dt)^{1/2}$ follows in the order of one millimetre. This means nothing more than the additional heat loss from the wafer edge due to heat radiation influencing mainly the temperature distribution within a millimetre wide outer ring of the wafer. The factor, by which the heat radiation near the edge region increases, is equal to the ratio between the surface area of the ring under and without consideration of the edge area of the ring. Taking this into account one can estimate that the temperature of the millimetre wide ring region decreases within 0.1 s after the pulse on average by about 80°, in comparison to 70° in the central area. Obviously, the relatively large temperature difference of about 10° over a distance of 1 mm seems to be sufficient to orient the dendritic crystal growth from the edge toward the wafer centre. In fact, small dendritic islands were observed after the pulse treatment in the edge region of samples of series-A. However, the majority of the liquefied film was agglomerated in form of small droplets. The film agglomeration is associated with the insufficient wettability of silicon dioxide by liquid silicon. Consequently, with the aim to extend the dendritic regions over larger areas, first the wettability of SiO_2 by liquid silicon has to be improved, but second, the lateral growth velocity has to be kept high also in regions, where the lateral temperature gradient is quite low, i.e. far from the wafer edge.

As will be shown, the key to solve the aforementioned challenges is the admixture of an impurity to silicon, having the following properties. First, it has a much higher solubility in liquid, than in the solid silicon, thus enriches on the liquid side of the solidification front. Second, the impurity improves the wetting behaviour of silicon dioxide in relation to liquid silicon and third, the addition of the impurity leads to a significant increase of the silicon melting temperature. As a consequence, before the crystallisation front the conditions are fulfilled to initiate dendritic crystal growth due to constitutional under cooling of the liquid silicon.

Carbon is a good candidate to fulfil all requirements. It has low equilibrium solubility in silicon. Near the silicon melting temperature it amounts to $\sim 3.5 \times 10^{17}/cm^3$ in the solid and $\sim 9.1 \times 10^{18}/cm^3$ in the liquid phase [11]. Furthermore, carbon has a strong influence on the silicon melting temperature. For example, already one per cent carbon admixture increases the silicon melting temperature by about 100 K. Additionally, carbon, as element of the same group, has only low influence on the carrier concentration in silicon and, adjusting the orientation parallel to the grain boundaries, the transistor channel mobility will be less affected as well. Finally, the carbon enrichment near the SiO_2 interface improves the wetting behaviour of SiO_2 [12]. This fact can be attributed to the formation of a silicon carbide layer near the interface during the heat treatment. Thereby, similar to the well known from industry Acheson process [13] for the production of silicon carbide, carbon react at high temperatures with SiO_2, forming SiC and CO, but silicon carbide then again has a good wettability to silicon melt [12]. In the present experiments high dose ion implantation was used to introduce the carbon atoms into the layer (series-B).

3. Results and discussion

3.1. Unimplanted samples (series-A)

First, a set of unimplanted samples was irradiated with 20 ms light pulses of different energy densities, but constant preheating for one minute at a temperature of 700 °C. We observed that above an energy density of 110 J/cm^2 the top surface of the silicon layer begins to melt, resulting in a more or less hilly surface relief, but without a significant effect on the grain size. However, after the energy density was increased above a value, sufficient to melt the silicon layer over its total thickness, the picture changes dramatically. Owing to the fact, that liquid silicon does not wet silicon dioxide [14], the film, after it is molten completely, resolves into small spherules or lines with dimensions in the range of 1–5 μm, even though the melting time is relatively short. Fig. 1 shows an optical micrograph of the surface after irradiation with an energy density of 120 J/cm^2. The dark area in the figure corresponds to a region, where the whole layer was molten and agglomeration of silicon takes place. Only on the left side in the micrograph a small dendritic region is seen, which merges into a partly molten polycrystalline island. Based on these experiments it seems obvious, that, for large area melting, in the first order the wetting of the underlying silicon dioxide by molten silicon has to be improved.

3.2. Carbon implanted samples (series-B)

The carbon implanted samples (series-B) were irradiated under the same conditions as series-A samples without carbon. At energy densities above 110 J/cm^2 (not shown) they show a similar surface relief to those of the unimplanted samples. This is not surprising, as only the surface starts melting; however the carbon atoms are located in deeper regions of the layer. In contrast, Fig. 2 represents

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