TEM Study of Implanted Silicon Applied to Piezoresistors Manufacturing

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High quality piezoresistors require a p-n junction of very low leakage current. In order to obtain a p-n junction, n-type silicon wafer can be implanted with B⁺ ions and subsequently annealed. After implantation the silicon wafer is highly damaged. During successive annealings the crystalline lattice is restored and the boron profile is broadened. The residual defects always occur (Fig. 1).

The amount of residual defects can be however distinctly reduced when amorphization is applied just before boron implantation. When the appropriate implantation energy, dose and substrate temperature are used, ion implantation results in the formation of an amorphous layer [1]. Recrystallization is activated above 550°C and is slow at lower temperatures. However when amorphous zones do not create the continuous layer, the activation energy can be lower [2]. Appropriate annealing of amorphized silicon leads to complete recrystallization and results in a low defect-density.

The technological processes of preamorphization and boron implantation were investigated by means of transmission electron microscopy (TEM). In order to obtain a low defect-density, the n-type (100) oriented Czochralski-grown silicon wafer was first implanted with ¹⁹F⁺ ions. Depending on implantation energy an amorphous surface layer or a buried layer are observed (Fig. 2a, Fig. 2b). When the amorphous region is well-defined, annealing at 600°C for 1h in nitrogen atmosphere results in the complete recrystallization and the formation of two defected layers. The lower defected area evolves from the end-of-range defects and is the residue of the amorphous silicon-crystalline silicon interface [1,3]. The Cross-sectional TEM image (XTEM) of amorphized silicon (70 keV, 3·10¹⁵ cm⁻² – see Fig. 2b) and annealed at 600°C for 1h in N₂ atmosphere is presented in Fig. 3a.

When the energy is too high a fluorine implantation results in the formation of a buried, highly damaged area, which is not truly amorphous (Fig. 2c). Subsequent annealing at 600°C for 1h does not result in the formation of well-defined defected layers.

The sample of which XTEM image is presented at Fig. 2c was subjected to second fluorine implantation with lower energy and lower dose (40 keV, 1·10¹⁵ cm⁻²) – Fig. 2d. After the second implantation, the damage in the sample is not increased, furthermore – ion beam heating restores the crystalline lattice previously damaged. Fig. 3b shows the XTEM image of this sample annealed at 600°C for 1h. The recrystallization of an amorphous silicon layer induced by ion implantation has been discussed in recent papers [4].

Primarily amorphized specimens were, afterwards, implanted with B⁺ ions (40 keV, 3·10¹⁴ cm⁻²) and subjected to multi-step furnace annealing 600°C(3h)/800°C(1h)/1100°C(2h). The samples preamorphized by fluorine implants of 70 keV, 3·10¹⁵ cm⁻² (Fig. 2b) revealed the best electrical properties. XTEM images of these samples (after complete thermal process) showed no extended defects except the area spreading 400 nm from the surface. Samples implanted only with boron without amorphizing fluorine implantation (Fig. 1) show the defects extending to the depths of about 3 μm. The presence of the dislocations in these areas increases leakage current and depreciate the quality of the p-n junction. Application of the fluorine implantation with proper energy and dose is reasonable: it improves junction quality.
Fig 1. XTEM image of silicon implanted with boron (40 keV, $3 \times 10^{14}$ cm$^{-2}$) after sequential multi-step furnace annealing 600°C(3h)/800°C(1h)/1100°C(2h) in N$_2$ atmosphere.

Fig 2. XTEM images of silicon implanted with $^{19}$F$^+$ ions: (a) 35 keV, $3 \times 10^{15}$ cm$^{-2}$, (b) 70 keV, $3 \times 10^{15}$ cm$^{-2}$, (c) 90 keV, $3 \times 10^{15}$ cm$^{-2}$, (d) 90 keV, $3 \times 10^{15}$ cm$^{-2}$ and 40 keV, $1 \times 10^{15}$ cm$^{-2}$.

Fig 3. XTEM images of silicon implanted with $^{19}$F$^+$ ions and annealed at 600°C for 1h in N$_2$ atmosphere: (a) 70 keV, $3 \times 10^{15}$ cm$^{-2}$, (b) 90 keV, $3 \times 10^{15}$ cm$^{-2}$ and 40 keV, $1 \times 10^{15}$ cm$^{-2}$.