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Energy filter for tailoring depth profiles in semiconductor doping application

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ABSTRACT

This work presents the physics and technology of a micromechanically fabricated "energy filter" for doping applications. This energy filter is capable of producing pre-defined tailored doping profiles by a single monoenergetic ion implantation. The functional principle of the energy filter is explained using a simple model. Pattern transfer is being investigated for two different filter-substrate distances. Different aspects of the filter's temperature behavior during irradiation are discussed. Finally, the results of an entire wafer area implantation are presented and discussed.

1. Introduction

The vast increase of worldwide energy consumption has been pushing the development for highly efficient semiconductor power devices like e.g. high voltage Schottky diodes. Compared to silicon (Si), silicon carbide (SiC) has a wider band gap, larger critical field strength and better thermal conductivity. The production of high voltage SiC Schottky diodes requires a homogenous well defined dopant depth profile. Doping during epitaxial deposition of the active device layer is state of the art, however variation of the dopant concentration of about ±25% is usually obtained [1]. It is generally known that a more accurate doping is provided by ion implantation, reaching easily a doping homogeneity well below ±5%, even for high volume production and large wafer sizes. For the case of Si a homogeneous depth-profile in the range of some micrometers can be created by multiple ion implantation followed by thermal processing. However in SiC this method is not applicable, as the diffusion constant of the n-type dopant nitrogen, as well as that of many other impurities, is extremely low even at very high temperatures [2]. The use of an energy filter [3,4] able to produce a pre-defined tailored dopant depth-profile via a single monoenergetic ion implantation offers a suitable workaround. In particle tumor therapy, similar filters have been in use for long [5,6]. In this paper we present the energy-filter-implantation (EFI) technique. The working principle is presented and simulation results for different substrate materials are shown. The lateral homogeneity of the dopant profile is experimentally proven for given implantation conditions. The implantation depth profile is shown for different implantation conditions and finally the heating of the filter as a function of the beam current is determined. Finally the experiments are summarized.

2. Principle of the energy filter method

The basic principle of the energy filter can easily be explained by analyzing the ion tracks, as displayed in Fig. 1. The filter prongs transform the monoenergetic incident ion beam into an ion beam with a broad energy distribution due to energy loss of ions along their individual paths in the filter. As ion 1 travels the minimum distance within the filter material, a maximum implantation depth in the substrate is achieved (solid line). Ion 2 travels the longest distance within the filter, which causes a minimal implantation depth (dashed line). All other ion trajectories are in between. Thus the energy filter changes a monoenergetic ion beam's typical Gaussian implantation distribution into a rectangular shaped profile. The supporting layer shifts the energy distribution by a constant offset. The lateral homogeneity

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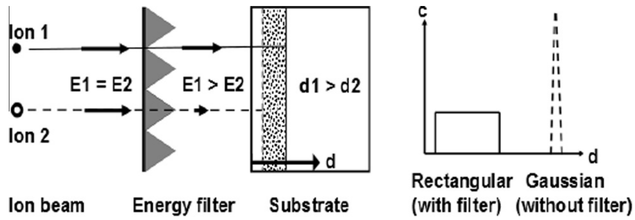

Fig. 1. (Left side) Basic principle of a triangular energy filter with supporting layer. (Right side) Corresponding implantation profile with filter and without the filter where E is the ion energy, d is the depth and c is the dopant concentration. $E1$, $E2$, $d1$, $d2$ denote energy and projected range of ion 1 and ion 2 respectively.

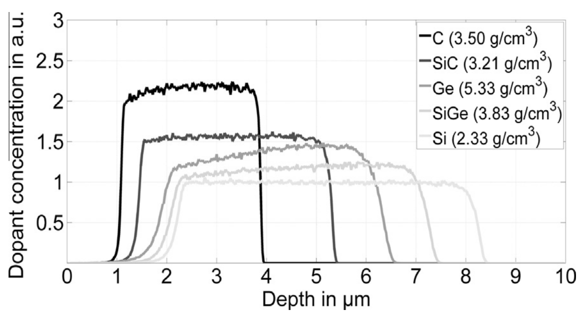

Fig. 2. Implantation profiles of 7 MeV boron ions with an triangular filter structure (supporting layer 1 µm, 6 µm base length) for different substrates materials simulated with Iradina [7]. The substrate material density for the simulation calculations is given in the legend.

of the doping profile across a wafer is influenced by the filter-substrate distance. Experimental data addressing this issue will be presented in Section 4.

Fig. 2 shows the depth profiles of 7 MeV boron implants into different substrate materials for a Si filter with 6 µm base length, triangles' slope angle 54.74° and with a supporting layer of 1 µm as simulated with the Iradina code [7]. In the simulation lateral homogenity of the transmitted ion concentration is assumed. The validity of this approach is supported by experimental results presented in Section 4 and by [3,8]. The dopant depth profiles are strongly influenced by the energy dependence of the stopping power of the selected substrate material. A deviation from the rectangular shape appears due to differences in the functional dependency of the stopping power with respect to the Si filter material. Compared to Si as a substrate all other selected materials show a compressed depth range and a shift towards the surface which is caused by the higher stopping power of the respective material. For a simple triangular shaped design only the combination of Si as filter material and Si as substrate material will yield a flat homogeneous profile. However, as shown in Fig. 3 for identical filter and substrate materials, the design of the filter (height, shape and areal fill factor of stopping structures) can be used to tailor the shape and vertical position of the dopant profile and thus control the effect of material choice on the profile.

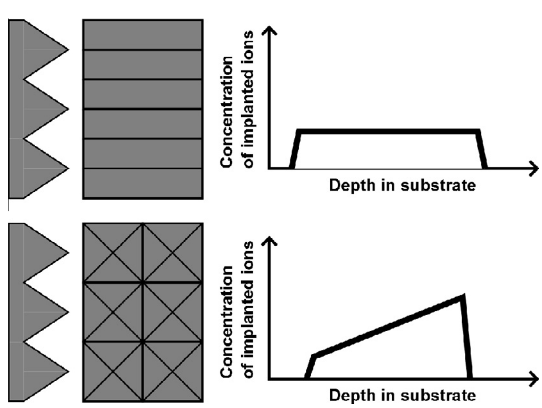

Fig. 3. Impact of microstructure design on implantation profile, for equal filter substrate material combinations.

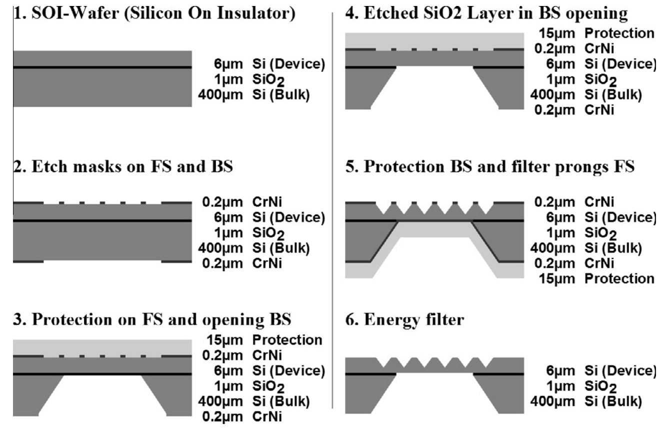

Fig. 4. Sketch of the energy filter fabrication process. FS/BS – front side/back side.

3. Filter manufacturing and structure

The filter fabrication sequence is illustrated in Fig. 4. A 3″ Si on insulator (SOI) wafer is used as substrate. The front side (FS) and back side (BS) of the wafer are patterned with CrNi via lift-off and CrNi-etch respectively (2). After opening the BS via etching with 40% KOH solution at 80 °C (3) and using the SiO_2 layer as the etch stop, the oxide is removed via HF-etch (4). Afterwards the filter prongs are etched into the FS (5). After removal of etch masks and protective coating, the energy filter with a total chip size of 26 × 26 mm^2 is finished (6). The filter membrane has a size of 8 × 8 mm^2 and the surrounding bulk material frame has a thickness of 400 µm.

As displayed in Fig. 5, a Si filter with a 2 µm supporting layer and trapezoidal microstructure is used for the implantation experiments in this work. The trapezoid has a height of 4 µm, a periodicity of 8.42 µm and a slope angle of 54.74°. Unlike the ideal triangular structure, in our experiment the dopant profile is additionally modified by the top plane on the trapezoidal microstructure which is perpendicular to the ion beam. Thus ions with lower energy are favored after the transmission through the filter resulting in a peak at the beginning of the implantation profile (see Fig. 7). The structure is arranged as a regular pattern of long lines across the membrane.

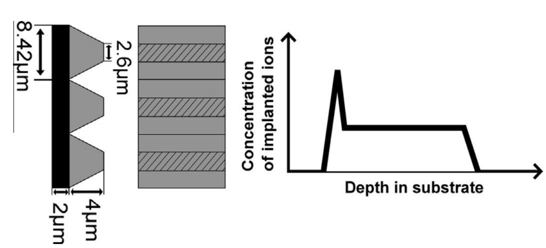

Fig. 5. Schematic cross section of trapezoidal filter and resulting implantation profile for equal filter substrate materials.