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Atomic Force Microscope Study of Two-Dimensional Dopant Delineation by Selective Chemical Etching

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1. Introduction

The reduction of semiconductor device dimensions to the submicron level could be achieved by the employment of very light implant conditions to produce shallow junctions. The fabrication of such devices requires a precise control of the total amount of dopants and quantitative information concerning one-dimensional (1-D) and two-dimensional (2-D) dopant distributions. A variety of techniques such as transmission electron microscopy (TEM) [1-2], scanning electron microscopy (SEM) [3-4], scanning tunnelling microscopy (STM) [5] and atomic force microscopy (AFM) [6] have been successfully employed to obtain experimental 2-D data of dopants in semiconductor devices. A basic idea of these techniques is related to a combination of the selective-chemical etching of the doped layers and microscope examination; the characteristic of this technique is to image the etched surface using electron microscopes. The chemical etchant for silicon dissolution is a mixture of nitric (HNO_3) and hydrofluoric (HF) acids. The nitric acid reacts with the silicon surface to form oxides which are removed by the hydrofluoric acid. This process is faster at regions with higher dopant concentrations [7-10]. In this work, we present selective chemical etching and atomic force microscope (AFM) examination of p/n-type well regions and p/n-type junction areas defined with different implant conditions. Results obtained from different conditions are compared to the secondary ion mass spectroscopy (SIMS) and a TRIM simulation result. The two-dimensional etching profile could be resolved with a spatial resolution better than 10 nm.

2. Experiment

Two wells (n- and p-types) were fabricated in <100>-oriented p-type silicon wafers by the three-step-implantation of phosphorus and boron at energies ranging from 1.3MeV to 20keV (with a dose in the range of $1.6\times10^{12}cm^{-2}$ – $2.0\times10^{13}cm^{-2}$). Three sources and drains were fabricated on either the p-wells or n-wells by the implantation of arsenic, BF_2, and phosphorus at 40keV (with a dose ranging from $1.5\times10^{13}cm^{-2}$ – $3.0\times10^{15}cm^{-2}$). All the samples were then annealed at 850°C for 1.5h. In this work, different chemical solutions were used to delineate n-type and p-type regions. The chemical solution was a mixture of HF (40%), HNO_3 (65%), and CH_3COOH (99.5%) maintained at room temperature. The principal of the chemical reactions is given as follows [11],

$$Si+2HNO_3+6HF \longrightarrow H_2SiF_6+2HNO_2+2H_2O \quad (1)$$

This etching process is faster at regions with higher dopant concentrations.

For the delineation of p-type regions, the etching process was performed using a solution of $HF:HNO_3:CH_3COOH$ (1:3:8) under UV illumination with a 300W lamp. For n-type regions, however, a solution of $HF:HNO_3:CH_3COOH$ (1:100:25) without UV illumination was used. After etching, the samples were thoroughly rinsed in deionized water to completely stop the etching process. The topography of the etched surface was then characterized using AFM (Park Scientific Instruments, Inc.) with a silicon nitride tip.

3. Results and Discussion

A typical AFM image of a n-well sample etched for 4 seconds is shown in Fig.1. The depth of the etching profile appeared to be slightly irregular. Some isoconcentration contours and the lateral carrier profiles are clearly visible.

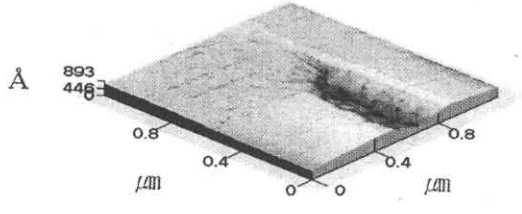

FIG.1 AFM topography of a n-well implanted with phosphorus, which was etched using a solution of $HF:HNO_3:CH_3COOH$ (1:100:25) for 4 seconds.

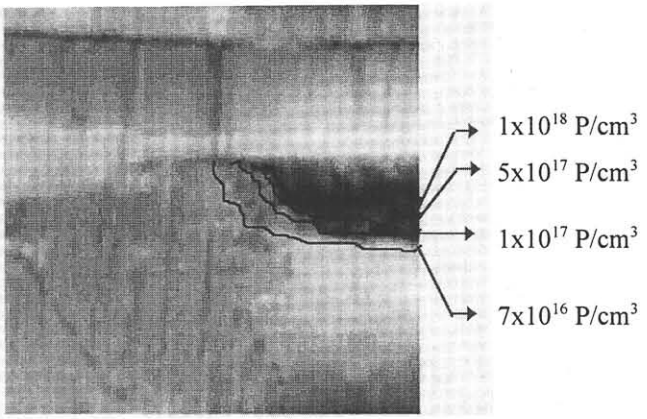

FIG. 2 AFM top view of a n-well implanted with phosphorus showing two-dimensional etching profile below silicon oxide.

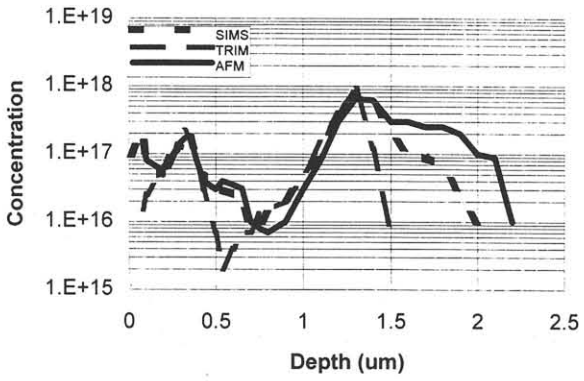

FIG. 3 Vertical dopant concentration profiles of p-well using SIMS, TRIM simulator, and AFM.

The isoconcentration contours arise from the differences in the etching rates which depend on dopant concentrations. Selectivity is very sensitive to the etching rate as well as the etching time. Properly short etching times is needed for delineation since longer etching time leads to the roughening of the surface, i.e. a decreased selectivity. The extension of the etched region is about 0.35μm from the oxide layer of the sample [Fig.1].

Calibration of the etched depth as a function of the carrier concentration was obtained using uniformly doped silicon wafers with concentrations in the range $1x10^{16}$–$1x10^{21}cm^{-3}$. Such a calibration enable us to deconvolute the AFM topography of an etched surface to a carrier concentration image. Correlation between the etching rates and dopant concentrations of the phosphorus doped region is shown in Fig.2. Calibration shows that the dopant concentration can be delineated down to a concentration of $7x10^{16}cm^{-3}$.

As for the delineation of a P-type (boron-doped) region, a chemical solution of $HF:HNO_3:CH_3COOH$ (1:3:8) was usually used. The etching was performed for 6 seconds under UV illumination. Although the UV-light-aid selectivity is not well understood yet, such improvements was related to the chemistry of the etching process and possibly to the mobility of the carriers, since different etching rates were observed for n-type versus p-type samples.

In Fig.3 are shown the vertical boron-dopant profiles determined by SIMS, TRIM simulation and AFM. Dopant profile obtained by selective chemical etching method is well resolved and is in good agreement with that of the SIMS. The profile is, however, slightly different from the TRIM simulation results in the deeper region. This is probably related to the channeling effects. For TRIM simulation, such effects was not taken into account. It is also interesting to note the presence of the three peaks in the profiles due to the implantation conditions.

As for the delineation of other samples, the selective chemical methods were also successfully employed and the dopant concentrations were shown to be delineated down to a concentration of $\sim 10^{17}cm^{-3}$.

4. Summary

AFM examination coupled with selective chemical etching were carried out on p-type and n-type doped regions to delineate dopant profiles. The selectivity was strongly dependent on the types of dopants and the etching time. Calibration showed that the carrier concentration can be delineated down to a concentration of $\sim 1x10^{17}cm^{-3}$.

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