Depth Measurement of Nanoscale Damage to the Surface of Silicon Wafers in the Production of Submicron Integrated Microcircuits by Auger Spectroscopy Method

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***Abstract*—The proposed method of depth control of the damaged layer of the polished wafers, based on application of Auger spectroscopy with the precision sputtering of the surface silicon layers and registration of the Auger electrons yield intensity from the wafer surface. The method makes it possible to perform the efficient depth control of the damaged layer and thus ensures the reliable control under the production conditions. The depth measurement range of the damaged layer constitutes 0,001–1 um. Resolution by depth is 1 nm.**

Keywords*—*polished wafers, damaged layer, Auger electron, depth of the damaged layer formatting

I. Introduction

The main trend in the development of modern microelectronics is a constant and rapid reduction in design standards. Intensive transition to submicron microchip manufacturing (IC) technologies causes higher requirements for the used materials and the formation of silicon wafers with improved properties in a thin near-surface layer becomes actual. The depth of the surface damage (the depth of the damaged layer) of silicon wafers is their most important parameter, which must be controlled in the manufacture of IC. The surface damage occurs as a result of mechanical influences at the stage of wafer manufacture, and as a result of radiation processes, in particular, during ion implantation of the dopant. Knowledge of the depth of the damaged layer allows to optimize the processes of silicon processing and choose the best of them, which in turn increases the yield and reduces the consumption of materials.

There is a large number of methods for monitoring and determining the parameters of the damaged layer [1-4]. However, there are no universal methods for controlling the depth of the damaged layer, its individual composite zones, and defects in the crystal silicon lattice. The process of investigating the depth of the damaged layer of silicon wafers consists of several stages, including the application of both methods sensitive to defects in the crystal structure and methods of layered removal of these violations. Large violations, for example, after cutting the ingot onto wafers, where the depth of the damaged layer is tens of microns, can be measured with relatively simple methods with sufficient accuracy. The damaged layer after polishing is 1-5 μm, and its measurements are no longer so unambiguous. In these cases, more modern methods with higher resolution should be used. To control the depth of the damaged layer of silicon wafers after polishing (<0.5 μm), there are practically no quantitative methods for estimating it. Known modern methods are very laborious and not suitable for industrial use. The object of the study in this work is a damaged layer on the surface of silicon wafers intended for the production of submicron IC. The aim of the work is to develop an effective method for controlling the depth of the damaged layer of silicon wafers after chemical-mechanical polishing with the use of modern analytical tools.

II. Physical Basis and Essence of Method

In this paper, there is proposed a new quantitative control method of damaged layer depth of silicon wafers after polishing for ICs of submicron sizes. The method is based on the use of Auger spectroscopy with precision sputtering to surface silicon layers and registration of yield intensity of Auger electron from the wafer surface [5–7]. To measure the depth of damaged layer using Auger spectroscopy, the dependence of the number of emerging Auger electrons on the sputter time (profile) is removed, and then this dependence is analyzed (Fig. 1).

The quantity of silicon in a damaged layer is less than in the volume. With deepening, the damaged layer decreases, which corresponds to an increase in density of atoms in a single layer. On the graphs Fig. 1 this corresponds to a smooth exit to the plateau.

The essence of a methods consists in the fact that the damaged layer is removed by ion beam sputtering and the interface is detected by recording the intensity of the Auger electron yield from the atomized surface until it reaches a value equal to the yield of Auger electrons for single crystal silicon, and the depth of the damaged layer is determined by measuring the height of the step, formed as a result of removal of the damaged layer from the surface of the silicon wafer [8-13].

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The registration of yield intensity of Auger electrons from the silicon surface while removal of silicon surface layers allows control efficiently the presence of a damaged layer on silicon wafer surface. And the depth control locality (averaging by depth) because of the specifics of Auger spectroscopy is 1 nm. The intensity of the Auger electron yield is determined automatically on the Auger spectrometer and gradually increases with the removal of the damaged layer. After removal of the damaged layer, the value of the yield intensity reaches a maximum value equal to the value for single crystal silicon (silicon without a damaged layer), with a depth error not exceeding ± 1.0 nm, and further removal of the surface layers of silicon ceases. Thus, a step is formed on the surface of the sample: on the upper part of it there is the initial surface of the analyzed silicon wafer with the damaged layer, and on the lower part - the surface with the removed damaged layer. The value of this step is equal to the depth of the damaged layer.

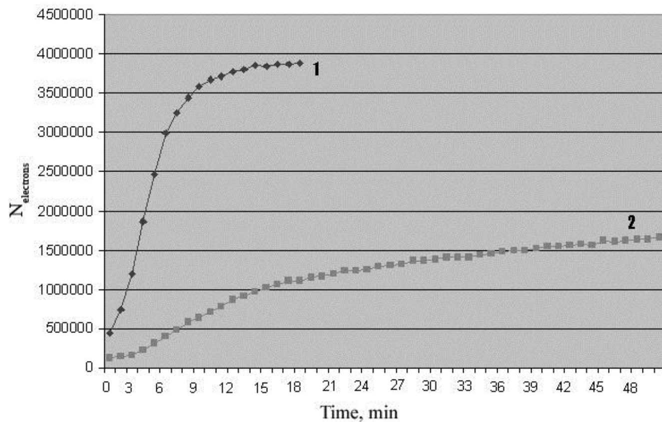

Fig. 1. The dependence of the amount of the emanating Auger electrons from sputtering time for the wafers after polishing (1) and grinding (2).

The use of Auger spectroscopy to determine the depth of the damaged layer of silicon wafers is due to two circumstances:

- the possibility of successive removal of thin, down to monatomic, layers;

- the yield of Auger electrons depends on the amount (density) of the analyzed material on the surface. Since there are many defects in the damaged layer, its density will be less than that of a single crystal material and, consequently, the number of emerging Auger electrons will be smaller.

The depth of the damaged layer was determined from the step on the profilometer after the complete removal of the damaged layer by sputtering. The wedging out on single crystal silicon was determined as follows. The control of the intensity of the Auger electron yield was made after each sputtering step. When the yield of electrons in three steps did not change by more than one percent, the sputtering ceased, the sample was taken from the spectrometer chamber and the depth of the crater at the profilometer was measured. The Talystep profilometer, which was used in the work, has a maximum vertical increase of 2000000 times. With this increase, the minimum fission rate is 0.5 nm/mm. Fig. 2 shows an image of a real step of 100 nm on a chart tape of a profilometer. This step was measured with an increase of 200000 times and its size on the profilometer tape is 20 mm. These data clearly illustrate the capabilities of the profilometer.

Auger spectrometer PHI-660 allows to change the sputter speed in a very wide range: from tenths of a nanometer per minute to 100 nm per minute. Therefore, if the depth of the damaged layer is small, variations in the sputter speed can reveal differences in the methods even of chemical-dynamic polishing.

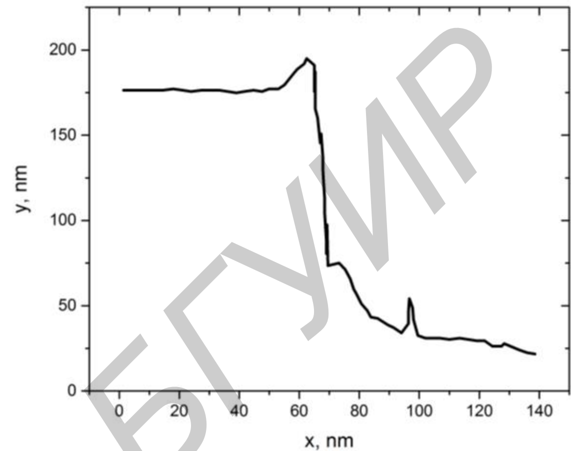

Fig. 2. The profile of the step on a profiler chart tape.

III. Method Metrological Characteristics

To determine the random component of the depth measurements of the crater, a series of measurements were performed on one sample with a crater depth of approximately 50 nm. The increase in the profilometer was set at 1,000,000 times. The value of the standard deviation of the measurement results did not exceed 1 nm. For this reason, the random component of a single measurement error with a confidence probability of 0.95 does not exceed 4%. With a decrease in the depth of the damaged layer, the error will increase. However, the method makes it possible to determine the depth of the damaged layer starting at a value of 1 nm. The depth of the damaged layer on the silicon polished wafer can not be smaller, since in the air a film of natural silicon oxide of 1-2 nm thickness is formed very quickly, which also enters the damaged layer.

The depth of the damaged layer can be determined from the known sputter speed. To do this, it is necessary to select the optimum sputter conditions for the sample, determine the sputter speed for this mode, and then use the fixed sputter modes and the value of the speed value. The sputter speed can be determined in two ways:

- sputtering a layer of known thickness. For example, the thickness of the silicon dioxide layer can be determined quite accurately by ellipsometry method. Taking into consideration that the sputter speed of silicon dioxide is practically the same as that of silicon, and the interface of silicon-silicon dioxide is

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reliably determined by the Auger spectrometer, the sputter speed in this case is determined quite accurately;

- repeated sputtering the silicon wafer, measuring the depth of the steps on the profilometer and calculating the sputter speed by statistical data processing.

It means that there is no need to constantly use the profilometer to measure the depth of the damaged layer. It is sufficient to adjust the Auger spectrometer to a known sputter speed and, by determining the time of yield to the single crystal silicon from the removed profile, to calculate the depth of the damaged layer.

To determine the optimal sputter speed, a number of experiments were carried out. In the course of these experiments, the parameters of the electron gun were varied: the ion beam current, the raster (scanning), and the slope of the sample. As a result, a sputter speed of 2.2 nm / min was chosen. The sputter modes were the following: a 3 x 3 mm raster, an accelerating voltage of 3.5 kV, an ion beam current of 30 nA, an angle between the ion beam and the sample surface - 10 °.

The proposed quantitative control of the damaged layer depth has the following characteristics: the measuring range of the damaged layer depth is 0.001 - 1 μm, the resolution in depth is up to 1 nm. This method can be used in combination with scanning probe microscopy.

IV. Experimental Results and Discussion

Fig. 3 shows the dependence of yield of Auger electron on the sputter time for two silicon wafers made on different factories and having different modes of finish surface processing.

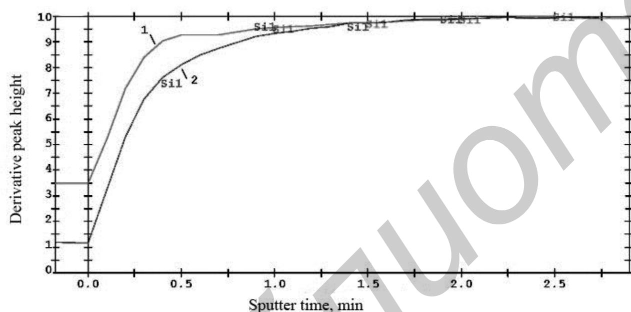

Fig. 3. The dependence of the relative magnitude of Auger electrons (derivative peak height) from the spray time of wafers №№ 1, 2, after different modes of the finish polishing: № 1 – wafer is manufactured in a foreign enterprise, № 2 – in Belarus.

Fig. 3 data analysis shows that the depth of a damaged layer does not completely reflect the quality of surface preparation. The time to single crystal silicon for wafers No. I, 2 is the same and is 1.75 minutes. This means that the depth of the damaged layer for the two wafers is the same and equal to 3.8 nm. It turns out that there is practically no difference between the wafers in the depth of the damaged layer. It follows from the data in Figure 3 that the damaged layers of the wafers differ. In the area of the damaged layer for wafer No. 1, the intensity of the Auger electron yield is much higher, and it can be assumed that it is more perfect in comparison with wafer No. 2. For this reason, it is suggested to additionally estimate the surface preparation quality over the area over the obtained sputter profile curve. It is reasonable to preliminarily convert the number of emerging Auger electrons in a relative amount. To do this, the measured amount of Auger electrons must be divided by the number of Auger electrons emerging from the single crystal silicon and then the area calculated. After carrying out the calculations, it turns out that for the wafer No. 1 the area above the obtained curve of the sputter profile is 0.191, and for the wafer No. 2 - 0.3323. It can be concluded that the surface quality of the wafer No. 1 is better than that of the wafer №2. The comparison of the yield of suitable submicron microcircuits shows that on the wafers of group No. 1 the yield is better than on the wafers of group No. 2, which is due to the difference in the quality of preparation of the wafer surface.

The use of Auger spectroscopy to measure the damaged layer depth after polishing and especially after cutting is inappropriate for several reasons: firstly, the sputter speed and time must be sharply increased; Secondly, there are methods for controlling the depth of the damaged surface layer after cutting and polishing are less laborious and fairly accurate [3].

The determination of the spread of the depth of the damaged layer from wafer to wafer for different wafer manufacturers showed that the minimum value of the depth of the damaged layer for polished wafers is 3 nm, and the maximum does not exceed 100 nm.

V. Conclusion

1. A method is proposed for measuring the depth of a disturbed layer on the surface of silicon wafers, based on the use of an Auger spectrometer with precision ion sputtering of silicon surface layers and recording the Auger electron yield. Range of measurement of the depth of violations 0.001-1 microns. Resolution at a depth is of 1 nm.

2. At equal depths of the damaged layer, the quality of preparation of the surface of the silicon wafer is suggested to be estimated over the area above the obtained curve of the sputtering profile.

3. The method is effective in optimizing the processes of finishing the surface of silicon wafers in microelectronic production, selecting the optimal technological processes, and helping to reduce the consumption of process materials.

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