A New Resonance Photoionization SNMS Instrument for Submicron Microarea Analysis

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We have developed a new resonance photoionization sputtered neutral mass spectrometry (SNMS) instrument for submicron microarea element analysis. The primary ion beam optical system which uses a liquid metal ion source (LMIS) was newly designed for the instrument, to achieve a beam diameter of less than 10 nm. The laser system for resonance ionization consists of two YAG (yttrium aluminum garnet) lasers and three YAG lasers pumped dye lasers. The mass spectrometer is a time-of-flight (TOF) reflectron type. Some test samples analyses were used to calculate useful yields. The calculated useful yields were more than 5%, which were at least two orders higher than when using Ga-SIMS. The sensitivity for submicron microarea analysis of the instrument is discussed.

1. Introduction

Secondary ion mass spectrometry (SIMS) is a powerful tool for characterizing semiconductor devices due to its great sensitivity. Advances in LSI technology, however, have required further improvement in spatial resolution and sensitivity. For instance, measuring 3-D dopant-atom profiles in ULSI devices has become increasingly important. However, the number of available atoms to measure in a submicron microarea of a ULSI device is very limited. Therefore, a high useful yield is very important for high-sensitivity analysis. In SIMS, the ionized fraction of the sputtered particles is less than 1%, and this results in low useful yields.

Photoionization sputtered neutral mass spectrometry (SNMS) with sufficient laser power can provide almost 100% ionization efficiency of sputtered neutral atoms. There are two kinds of photoionization of sputtered neutral atoms. One is non-resonance photoionization [1] the other is resonance photoionization [2,3]. Both types of photoionization can provide almost 100% ionization efficiency. However the photo-absorption cross-section of non-resonance photoionization is orders of magnitude smaller than that of resonance photoionization. In non-resonance photoionization the laser must be focused on a region of about 0.1 mm square in order for high ionization efficiency to be reached. Although ionization efficiency is high, laser beam irradiation efficiency to sputtered atoms is as low as about 10^{-4} so that useful yields are less than when using with SIMS. On the other hand in resonance photoionization the laser beam dose not need to be focused, and therefore irradiation efficiency of 20% can be obtained and useful yields of up to 1%-10% can be achieved which is much higher than when using SIMS. Resonance photoionization SNMS thus promises to provide greater sensitivity in microarea element analysis than SIMS. For this reason, we have developed a resonance photoionization SNMS instrument that incorporates a new focused ion beam optical system [4] which uses a liquid metal ion source (LMIS) for submicron microarea element analysis.

In this paper a new resonance photoionization SNMS instrument is described and the initial results are presented and then the sensitivity for submicron microarea analysis is discussed.

2. Instrument

This instrument is composed mainly by an ion beam optical system, a laser system, a TOF mass spectrometer, and a sample chamber.

A schematic diagram of the ion beam optical system is shown in Figure 1. The design of the optical system has been previously described in

detail [4,5]. The focused ion beam optical system mainly consists of two electrostatic lenses: a tetrode condenser lens and an einzel objective lens, each of which is made up of thin Butter-type lens electrodes.

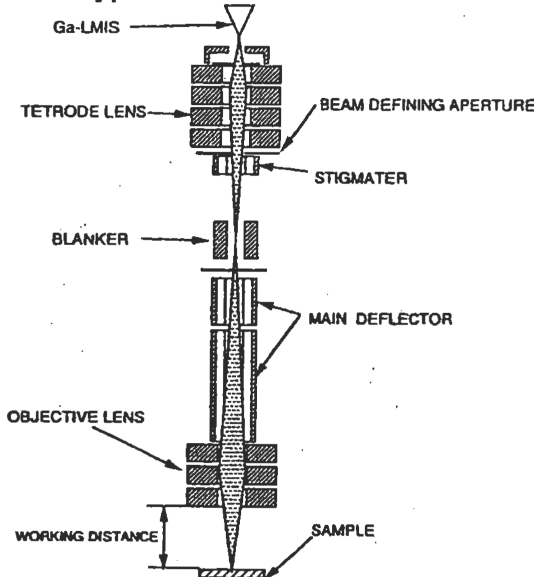

Figure 1. A schematic diagram of the ion beam optical system.

The axial performance of the optical system using a gallium (Ga) LMIS was calculated. Figure 2 shows the calculated beam diameter versus the beam current under the following conditions: the acceleration voltage is 40 kV; the working distance between the einzel object lens and a sample was 6 mm; and the thickness of the object lens was 8 mm. In the calculation it is assumed that there is: an extraction voltage

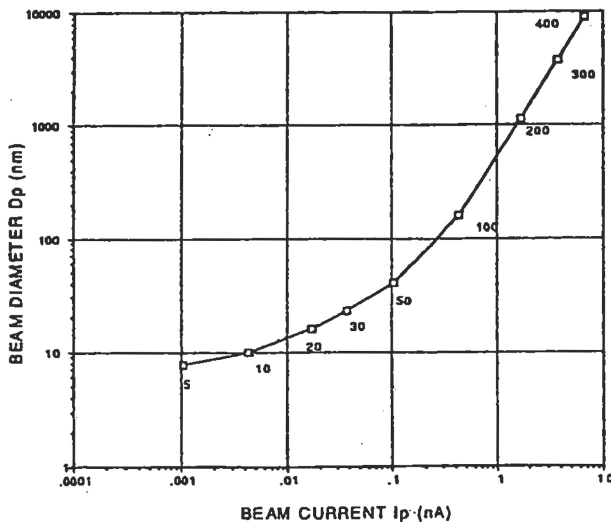

Figure 2. The calculated beam diameter versus the beam current of the new focused ion beam optical system. The numbers at each data point show the size of the aperture hole.

of 7 kV; angular current density of 15 A/steradian; an ion energy spread of 5 eV; and a virtual source diameter of 55 nm. The minimum beam diameter of less than 10 nm could be obtained, which is needed for microarea analysis of practical microdevices (e.g. a gigabit-scale DRAM whose minimum scale will be about 100 nm in the near future). Typical pulse length of the ion beam is 1 μsec. The laser system for resonance ionization consists of two Nd-YAG lasers (Continuum Power Light 9050) and three tunable Nd-YAG lasers pumped dye lasers (Lambda Physik Scanmate 2EY). Three laser beams in the 189-860 nm wavelength range can be obtained. A combination of the laser beams, (with a maximum of four colors from the dye lasers and YAG lasers) can be focused at the same time above a sample in the sample chamber. The YAG laser repetition rate is 50 Hz. The pulse width is about 8 nsec. The optical system (i.e. mirrors, prisms, and lenses) that transports the laser beams are set into the box. Then, the laser beams pass through aluminum pipes into the sample chamber. Typical pulse energies inside the sample chamber are several mJ.

The TOF mass spectrometer (Comstock) is called a reflectron type, it compensates energy distribution of ions with reflectron to improve a mass resolution. In the resonance ionization, selected element atoms are photoionized with high ionization efficiency. However, other elements atoms in a sample are also nonresonance photoionized with much lower ionization efficiency. Secondary ions of all elements also exist. The TOF mass spectrometer removes these nonresonance photoionized ions and the secondary ions of nonselected elements, because they are the background of the resonance ionized ion.

The timing control and data acquisition system contains a personal computer and CAMAC modules which are controlled by the personal computer.

The sample chamber is pumped by a 400l/s ion pump, and achieves a base pressure of 5×10^{-8} Pa. The ion beam intersects the sample plane at 60° with respect to the normal. The

sample is positioned about 6 mm from the extraction electrode of the mass spectrometer. The axis of the extraction electrode is perpendicular to the sample surface in order to improve the collection efficiency of photo-ions. In addition, the sample chamber has optical windows for laser beams. Also, the sample chamber is equipped with a duoplasmatron ion source and a pulsed electron gun for the electrical charge buildup compensation.

3. Results and discussion

Some test samples were analyzed in order to confirm the capability of the instrument for high-sensitivity microarea analysis.

Iron is an impure element which has the possibility causing ULSI devices to fail. Figure 3. shows the spectrum of the stainless steel under iron atom resonance ionization condition. Iron was excited using one ultraviolet photon (297 nm), and then ionized by an ultraviolet photon (297 nm); this is so called one-color resonance ionization [6]. The ratio of peak intensity in the spectrum shows that iron atoms were selectively ionized. Other components in the sample such as Cr and Mn were not ionized.

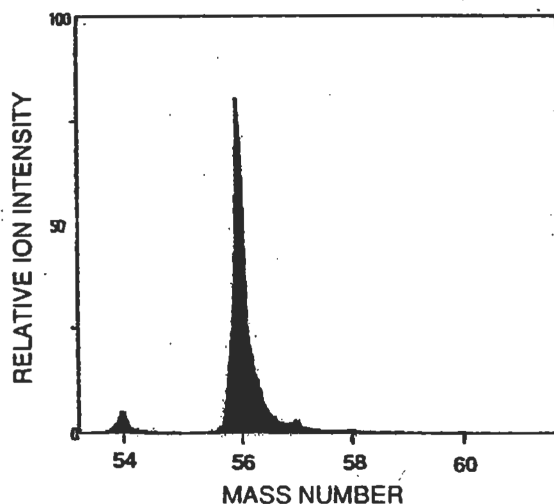

Figure 3. A typical spectrum of resonance photo-ionized iron.

Boron is one of the most important elements in a ULSI because it is used as a p-type dopant in silicon devices. Boron was excited using one ultraviolet photon (250nm) and by one visible photon (563nm), and then ionized by an infrared photon (1064nm); this is so called three-color resonance ionization [6]. An implant standard was used to calculate the useful yield for boron in silicon. The calculated useful yield was about 6%, which was about at least two orders higher than when using Ga-SIMS. Figure 4. shows the lateral profile of boron implanted through a patterned mask with a dose of 1×10^{15} atoms/cm^3 in silicon. The sample was analyzed with the Ga beam diameter of about 30 nm and a beam current of about 60 pA. The lateral profile was obtained from 3-D analysis. The detection limit of the lateral profile was lower than 10^{18}cm/atoms^3. This high-sensitivity microarea analysis was achieved because the high ion current density provided by the new focused ion beam optical system ensures that most atoms are available for resonance photoionization SNMS.

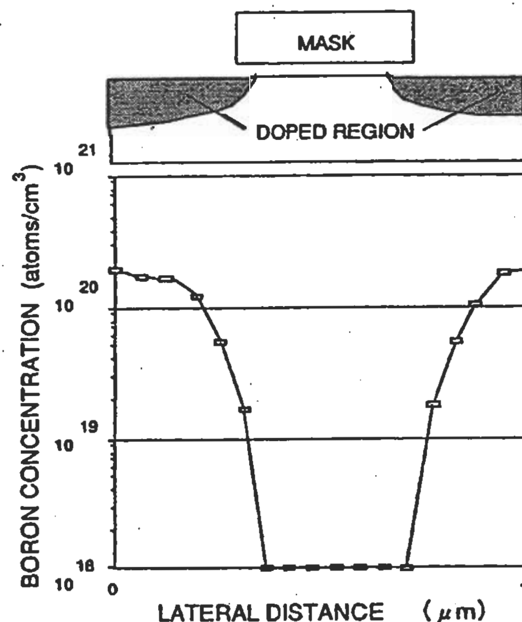

Figure 4. Lateral profile of boron implanted through a patterned mask in silicon.

When comparing the sensitivity of SIMS with that of laser phoionization SNMS, the duty cycle must be considered. SIMS with a magnetic sector mass spectrometer or a guadrupole mass spectrometer operate with unit duty factor, while this is not the case with laser phoionization SNMS. The duty factor is limited by the laser repetition rate of the pulsed lasers and the pulse width of the ion beam. The highest laser repetition rate of our instrument is 100 Hz. A 1μsec ion beam pulse width is typically used to achieve high irradiation efficiency. In this case the duty factor is 10^{-4}. In

a macroarea analysis e.g. a 0.1 mm square analysis which is usually done by SIMS, the unit duty factor of SIMS means that all atoms in the analysis volume are used although the ionized fraction of the sputtered particles is low. On the other hand, in laser photoionization SNMS when depth profiling to 1 μm deep, with a 1 μsec pulsed ion beam, and a 1 μA ion beam current which is typically the condition when using a duoplasmatron ion source or a Cs surface ionization source, the analysis time is more than 100 hours. In such a depth profiling by laser photoionization SNMS, two kinds of techniques are alternatively adopted. One technique is using alternate sputtering only and laser SNMS measurement. The other technique is using a much longer ion beam pulse width. However, using a longer ion beam pulse width cause lower irradiation efficiency. This means that all atoms in the analysis volume can not be effectively used for laser photoionization SNMS analysis. In fact, laser photoionization SNMS can only analyze less than 1% of the total number of sputtered atoms. These are reasons why even .resonance photoionization SNMS has not yet practically achieved a higher sensitivity analysis than SIMS. On the other hand, in microarea analysis (e.g. submicron square analysis which is practical the analysis of a ULSI device,) ion beams with a much higher ion current density of LMIS whose brightness are 4 orders higher than a conventional duoplasmatron ion source or a Cs surface ionization source, have the possibility making all atoms available for laser SNMS analysis. At an ion beam diameter of 30 nm and an ion beam current of 60 pA in the new optical system, with 1 μsec pulsed ion beam and a laser repetition rate of 100 Hz, it is possible that the region of 1 μm × 0.5 μm × 0.02 μm in a practical silicon microdevice can be analyzed within about 1 hour with a useful yield of 1-10%. This means the dopant profile can be analyzed with the detection limit of 1×10^{17} atoms/cm^3. This high sensitivity microarea analysis should be very helpful for the failure analysis or design of ULSI devices.

4. Conclusions

We have developed a new resonance photoionization sputtered neutral mass spectrometry (SNMS) instrument that incorporates a new focused ion beam optical system for submicron microarea element analysis. The useful yield was more than 5%, and a lateral profile of boron implanted through a patterned mask in silicon with a detection limit of lower than 10^{18} atoms/cm^3 was also obtained. We believe that the resonance photoionization SNMS will become a powerful tool for high-sensitivity analysis of practical microdevices such as ULSI devices.

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