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Focused Ion Beam Lithography- Overview and New Approaches

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Abstract – Focused Ion Beam (FIB) lithography has significant advantages over the electron beam counterpart in terms of resist sensitivity, backscattering and proximity effects. Applying the Top Surface Imaging (TSI) principal to FIB lithography could further enhance its capability. In this paper we review different FIB lithography processes which utilise both wet and dry development. As of further development of this technology, we report a novel lithography process which combines focused Ga^+ ion beam (Ga^+ FIB) exposure, silylation and oxygen dry etching. The Negative Resist Image by Dry Etching (NERIME) is a TSI scheme for DNQ/novolak based resists and can result in either positive or negative resist images depending on the extent of the ion beam exposure dose. The NERIME process can resolve nanometer resist patterns as small as 30nm yet maintaining high aspect ratio of up to 15. The proposed lithography scheme could be utilised for advanced prototype IC's fabrication and critical CMOS lithography process steps.

I. INTRODUCTION TO THE FIB TECHNOLOGY

The fabrication technology is the key to advance the current complementary metal-oxide-semiconductor (CMOS) technology and to realize new functional quantum devices such as electron wave and single electron transistors. During the years of IC's development, various nanofabrication techniques using photons, electrons and ions have been investigated. Focused ion beam (FIB) technology is one of the promising techniques for nanofabrication because of the distinct advantage of being a maskless process and providing a great flexibility and simplicity.

Since its introduction to the semiconductor industry in the early 1980's, FIB technology has been the mainstream tool for device analysis, repair and advanced specimen preparation [1]. Nowadays, FIB tools are commonly used in semiconductor, data storage and materials science industries. Various FIB applications have been developed for both removing (direct ion milling, FIB chemical etching) and depositing (ion implantation, FIB chemical deposition) a number of conductor and isolator materials with sub-micron precision [2]. The IC's device modification & characterisation by FIB has become a routine procedure at the manufacturing fabs by executing interconnects reroute and selectively deprocess of specific chip areas. FIB tools have also found wide applications in the secondary ion mass spectroscopy (SIMS) analysis.

II. FOCUSED ION BEAM LITHOGRAPHY

The use of finely focused ions as a direct patterning lithography technology was also studied in detail and has found great applications. Nowadays, the focused ion beam technology using liquid metal ion sources (LMIS) is considered as being a promising way for achieving high-resolution microfabrication [3]. Beam energy, spot size and current of most of the FIB systems range between 10 and 100 keV, 8 to 200nm, and 10pA to 10nA respectively [4]. Also, the invention of the LMIS has utilised very high current densities of $1A/cm^2$ and the use of different ion species such as Be^+, B^+, P^+, Si^+, Ar^+, Al^+, Ga^+, Au^+ [1, 4]. For the lithography applications, smaller beam size and higher current density are still desirable and continuous effort to meet these demands has been underway [2].

Among different FIB processes, three methods have been investigated for micro- and nanofabrication of advanced IC devices [4, 5]. These are the FIB direct milling, resist patterning with light ions and the dry development of FIB implanted resists. An overview of these techniques is given in the following sections.

A. Direct –write milling

Direct machining of the substrate by FIB is the simplest process for pattern fabrication. In this method, resist are eliminated and the dose of ions can be varied as a function of position on the wafer. It also utilizes the use of heavy ion species such as Ga^+ and Au^+.

FIB milling can be done very precisely on a substrate so to delineate the required topography. When an ion beam is scanned in a line on the surface, a trench is produced which initially has the shape of an inverse Gaussian as expected from the beam profile [1]. Usually one or two atoms are removed from the surface per incident ion. However, when the dose is increased, the trench becomes sharp, narrow and V-shaped. In addition, the shape of the milled feature is also dependent on whether it is obtained

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with a single scan or repetitive scans. A re-deposition process of the sputtered material is also observed on both sides of the milled trench. However, careful selection of the beam parameters could help minimizing these problems.

The direct FIB milling has been applied for the fabrication of various nanostructures including quantum wires and quantum point contacts in heterostructures, in-plane gate transistors and surface acoustic wave (SAW) devices in GaAs substrates [4,5]. Other applications include lithography mask repair and circuit microsurgery with resolution down to 100nm [1]. Opaque defects such as an excess metal on the chromium based masks can simply be milled off. Clear defects can be repaired by milling a light scattering structure (prism) into the area to be rendered opaque.

Another way of applying FIB milling to the lithography is by the use of bilayer structures. These structures usually made up of a thin gold layer on the top of conventional resist [5]. The gold layer is patterned by the use of Ga FIB milling and the sputtered pattern is transferred to the bottom layer by using reactive ion etching in oxygen plasma. This process has the advantage that the substrate is free from damage caused from ion bombardment.

B. Resist patterning with wet development

Ion beams of different elements can be used for direct resist patterning by depositing energy into a photoresist film similar to the electron beam exposure, followed by wet development process. Ion beams have the advantages of high-energy deposition rates and low scattering effects in the resist [5]. Therefore, conventional FIB lithography can be a high throughput, high resolution (nanometer) resist patterning process.

Ion beam lithography tends to minimise most of the problems related to the electron beam lithography, such as low resist sensitivity and stronger backscattering and proximity effects. The ion scattering in the resist layer and the backscattering from the substrate are negligible due to the much heavier particles mass. Also, the energy deposited per unit volume is much higher for ions in comparison with electrons [6]. It was reported that the dose needed to expose most resists by ions is about two orders of magnitude lower than for electrons [1]. The exposed resist patterns by the incident ion beams are limited only by the ion straggling, which laterally extends to a much smaller distance than the usual range of scattered electrons in case of electron beam lithography.

However, the conventional FIB lithography utilises light ions such as H^+, He^+, Be^+ and Si^+ due to the phenomenon of limited penetration depth of ions into the resist film. Light ions such as Be^+ and Si^+ have a penetration range of 1.2µm and 0.6µm respectively in the PMMA resist at 200keV energies [5]. By comparison, much heavier Ga^+ ions used in FIB lithography could only penetrate the top 100nm at 100keV [6], which is not deep enough to expose the entire resist thickness. Although the limited penetration range of ion can be utilised for specific lithography applications such as T-shaped gate formation [4], it significantly decrease the required resist thickness for conventional FIB lithography. The reduced thickness will result in low aspect ratio patterns and difficulties with further dry etching pattern transfer.

As a solution to this problem, the bilayer resist schemes for FIB lithography have been developed [5,6,7]. These schemes generally utilise a thin silicon-containing resist layer over a thick planarising layer. The top resist layer is exposed by FIB and wet developed, followed by transferring the patterns to the bulk layer via oxygen reactive Ion Etching (RIE) process. The regions where the silicon-containing resist layer remains are oxidised during the dry development, thus forming a silicon dioxide mask which protects the lower resist layer and results in positive image formation. Such FIB bilayer resist schemes are capable of achieving nanometer resolution while maintaining high aspect pattern ratio [6,7]. The only one drawback is the use of wet development step, which often results in resist swelling thus causing pattern deformation during the dry etching [4].

C. Resist exposure using dry development

FIB lithography which uses dry development will eliminate the need for wet processing and therefore the pattern deformation due to the swelling. It will also yield high aspect ratio structures with nanometer resolution.

There are several reports on the dry development of ion beam radiated resists for negative image formation. Resist regions where ions (Ga^+, Si^+) are implanted indicate significant reduction of the dry etching rate. These observations were explained with the formation of involatile compounds of the implanted species and the etching species, e.g. SF_6 plasma development of Ga^+ implanted titanium layers [8]. Another example of FIB dry lithography is oxygen plasma development of Ga^+ implanted spin-on glasses [1], where the exposed regions indicated up to 30% lower etching rate. Analogue effect, the ion beam inhibited etching, has been reported for patterning of PMMA photoresists by Si [9] or Ga [4] ion exposures. The resistance against oxygen RIE was explained with the view of formation of stable oxide layers, SiO_2 and Ga_2O_3, [4], and with the physical hardening of the resist called "graphitisation" [9].

III. NERIME PROCESS

The limited range of ions in resists is a perfect match for the Top Surface Imaging (TSI) processes, where the surface of the resist is selectively manipulated so to withstand oxygen dry development. Therefore, combining the FIB lithography with TSI and oxygen dry etching will further enhance its capabilities over the conventional lithography processes.

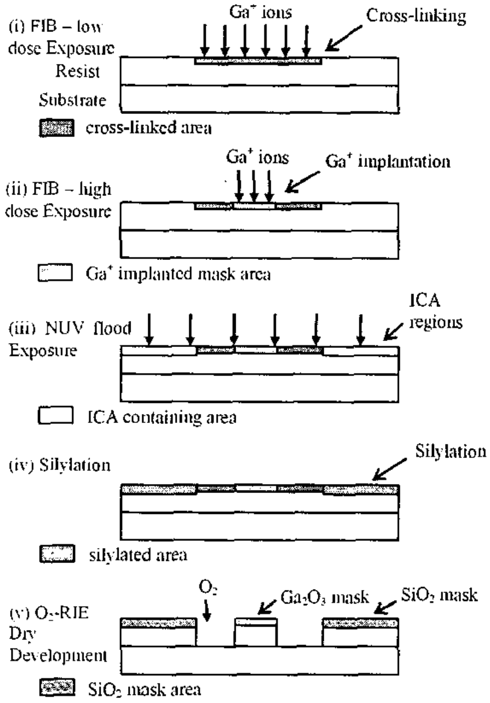

Fig.1: The NERIME process diagram.

The recently developed by the authors Negative Resist Image by Dry Etching (NERIME) process is a single layer TSI scheme for FIB lithography, which utilises both positive and negative image formation [10]. The newly developed scheme combines the best features from using FIB exposure and TSI approach in terms of nanometer resolution, negligible ion scattering and limited penetration depth. The underlying substrate layers are also kept out of damage by the exposing ions. The NERIME process also utilises high anisotropic processing of thick planarising resist layers thus raising the aspect ratio of the processed patterns.

The NERIME process implements FIB exposure, near UV exposure, liquid-phase silylation and oxygen RIE as shown in Fig.1. The scheme utilises two levels of Ga^+ FIB exposures of standard DNQ/novolak based resists. The low dose Ga^+ FIB exposure promotes crosslinkings into the exposed resist areas binding the photoactive compound (PAC) with the novolak resin chains. However, a second Ga^+ FIB exposure is then implemented, resulting in Ga^+ implantation of the exposed resist areas. The subsequent near ultraviolet (NUV) flood exposure convert the PAC to indene carboxylic acid (ICA) into the previously unexposed regions. Additionally, the resist surface is treated by silicon-containing chemicals (silylation process), which results in diffusion of the silylating agents into the ICA-containing regions and chemical reactions with the resin hydroxyl groups. By contrast, the diffusion into the FIB exposed regions is prohibited due to the presence of crosslinked structure. During the final oxygen RIE process, a thin SiO_2 layer is formed into the silylated regions thus protecting the resist underneath, while the crosslinked resist regions are etched away. Therefore, a positive resist image is formed into the exposed resist regions by low dose of Ga^+ ions. However, the ions implanted into the high dose exposed regions tend to oxidise in a similar way to the silylated regions, thus forming Ga_2O_3 mask. In result, such regions are retained after the etching representing negative image formation.

The NERIME process can also be simplified down to two steps by implementing only high dose Ga^+ FIB exposure and subsequent dry etching [11]. As a result, the Ga implanted resist areas will form a stable oxide mask which will yield a negative resist image after the etching.

A. Experimental results

NERIME experiments, carried out by the use of I-line resists Shipley SPR505A and SPR660, have indicated that Ga^+ FIB exposure with dose as low as $1\mu C/cm^2$ could prevent the resist from being silylated and therefore resulting in positive image formation after dry etching [10]. Fig.2 represents the exposure characteristics of SPR660 for the two-step NERIME process using Ga^+ FIB exposure and oxygen plasma development. It is evident that the negative image formation begins to delineate at exposure doses higher than $800\mu C/cm^2$ for 30keV acceleration voltage. The figure also demonstrates a comparison for the results obtained by [5], which uses similar lithography process to pattern the PMMA resists with Ga^+ exposure. In this case the ion beam dose required to form a negative image was estimated to be in excess of $3000\mu C/cm^2$. The authors also stated that in case of using DNQ/novolak based resists such as AZ1350, the critical ion beam dose must be as high as $10{,}000\mu C/cm^2$. Therefore, the two-step NERIME process results in much higher resist sensitivity and better process contrast than similar dry etching lithography schemes reported in the literature.

Experiments show that both the NERIME and the two-step NERIME lithography processes are capable of achieving high resolution down to the nanometer region by using even thicker resist layers. Fig.3 shows a perfectly

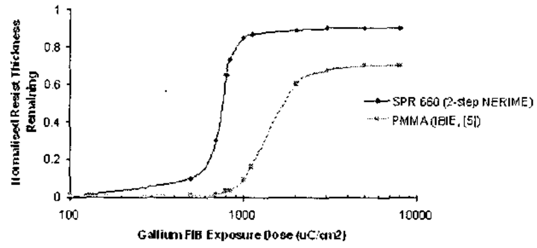

Fig.2: Exposure characteristics of Shipley SPR660 resist for the two-step NERIME process. Results from using similar process scheme, IBIE [5], are shown for comparison in case of negative tone patterning of PMMA resist.

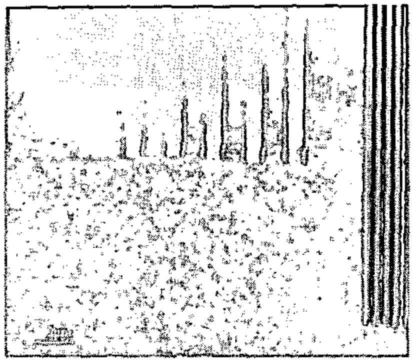

Fig.3: FIB image of 1μm lines/spaces and 0.1μm lines/spaces in *1.5μm thick SPR660 after the* NERIME *process.*

resolved gratings of 1μm lines/spaces and 100nm lines/spaces in 1.5μm thick SPR660. The NERIME process was performed with Ga^+ FIB dose of 5000 μC/cm^2 and $2.5x10^{-2}$ C/cm^2 respectively for the gratings, followed by a RIE dry development for 1000sec at 0.05mTorr oxygen pressure. The NERIME processed resist lines have also presented a greatly minimised line edge roughness (LER), as demonstrated in Fig.4, showing top-down FIB image of 100nm lines. The two-step NERIME process has also showed an excellent resist profiles with high anisotropic shape and vertical sidewalls, as demonstrated by the 100nm lines/spaces in Fig.5.

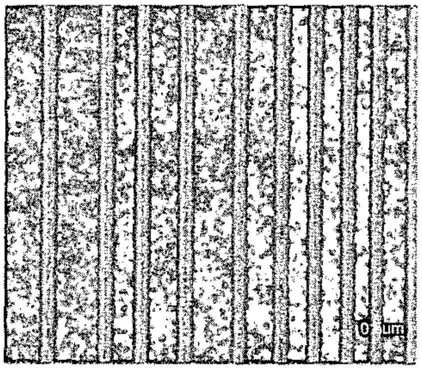

Fig.4: Top-down FIB image of 100nm SPR660 lines after the NERIME process, indicating minimal line edge roughness.

III. CONCLUSION

This article outlines the existing FIB lithography techniques and describes a novel dry developed lithography scheme that combines Ga^+ FIB exposure, silylation and oxygen reactive ion etching of single DNQ/novolak resist layers. The Negative Resist Image by Dry Etching (NERIME) process is a TSI scheme for sub-micron and nanometer lithography applications that can yield both positive and negative resist images depending on the extent of the Ga^+ ion beam exposure dose. Negative resist patterns with dimensions down to 100nm in SPR660 resist have been produced by the NERIME process, indicating highly anisotropic shapes with vertical resist sidewalls, minimal line edge roughness and high aspect ratio of up to 15. The NERIME and the two-step NERIME processes could be utilized for specific CMOS process steps such as high resolution lithography over topographical surfaces, and for lithography mask fabrication.

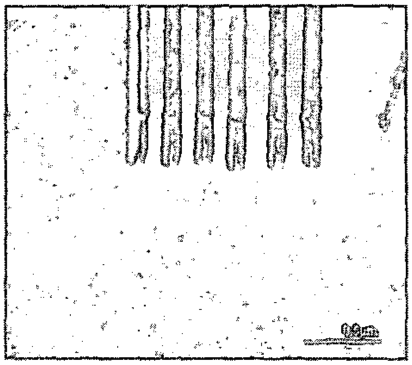

Fig.5: FIB image of 100nm lines/spacesspaces in 1.5μm thick *SPR660 resist after the two-step* NERIME *process, demonstrating* vertical resist sidewalls.

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