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Patterning Nanometer Resist Features on Planar & Topography Substrates Using The 2-Step NERIME FIB Top Surface Imaging Process

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Abstract

The 2-step negative resist image by dry etching (2-step NERIME) focused ion beam (FIB) top surface imaging (TSI) process has been previously reported as an excellent technique for patterning nanometer scale features in DNQ/novolak based photoresists on silicon substrates. In this paper we demonstrate that the 2-step NERIME process can be used to pattern nanometer scale resist features on different substrate materials and topography substrates.

1. Introduction

FIB technologies are widely used in advanced lithographic techniques to pattern small geometry integrated circuits and fabricate optical masks. An important FIB application is the direct lithography patterning of photoresists [1], [2].

Ion beams of different elements (Ga^+, H^+, He^+, Be^+, Al^+, Si^+) can be used to pattern resist by introducing energy into a resist film, followed by a wet or dry development process [3]. The introduction of energy into a resist film during ion beam lithography, by ion implantation, is similar to electron beam exposure during electron beam lithography.

FIB lithography has significant advantages over electron beam lithography in the areas of resist sensitivity, proximity and backscattering effects [2]. Distortions in submicron resist patterns due to resist loading effects have been found to be less significant with FIB exposure, when compared with electron beam exposure. The reduced proximity effects observed in FIB lithography are due to the fact that resist patterns exposed by ion beams are limited only by ion straggling, which has a much smaller distance associated with it than the range of scattered electrons during electron beam lithography [3]. FIB lithography can be successfully used to pattern resist critical dimensions (CDs) in the nanometer region.

The use of heavy ions in FIB lithography has its own set of limitations, such as slow writing speeds, limited penetration depth of ions into the resist film, and possible substrate damage during ion beam exposure. Ga^+ ions implanted at 100keV energies into resist have typical penetration depths of approximately 50nm.

To fully expose a resist layer using FIB lithography, very thin resist layers would be required. Thin resist layers and resultant small aspect ratio resist features can cause problems for subsequent processing steps such as plasma etching, where high resist aspect ratios and high etch selectivity to resist layers are desirable. TSI processing can provide a solution to the problem of low aspect ratio resist features in FIB lithography. In TSI schemes, the exposure does not need to penetrate the full thickness of the resist layer, but only a thin surface layer. Subsequent wet or dry processing develops away the unexposed resist, leaving only the exposed areas [4], [5]. TSI processes can overcome many common lithography problems such as low depth-of-focus and substrate topography effects.

The 2-step NERIME process is a single layer TSI scheme, using FIB exposure, optimised for DNQ/novolak based photoresists. The 2-step NERIME process combines the advantages of FIB lithography and TSI processing, and is capable of delivering nanometer scale resist CDs [6]-[11]. The 2-step NERIME process flow is shown in Fig. 1.

The first step of the 2-step NERIME process flow is the exposure of the DNQ/novolak resist film by the implantion of Ga^+ ions. Ga^+ was chosen because of its low penetration depth in resist, and this low penetration depth is consistent with TSI requirements. The Ga^+ is implanted into the resist layer to depths of between 10-50nm. The implanted

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resist regions will form a Ga_2O_3 mask during the oxygen plasma dry develop step of the process. The Ga_2O_3 regions have a much lower etch rate in oxygen plasma when compared with the unexposed resist areas. The difference in the etch rates between exposed and unexposed resist areas during the oxygen dry develop step results in the formation of a negative resist image in the resist layer.

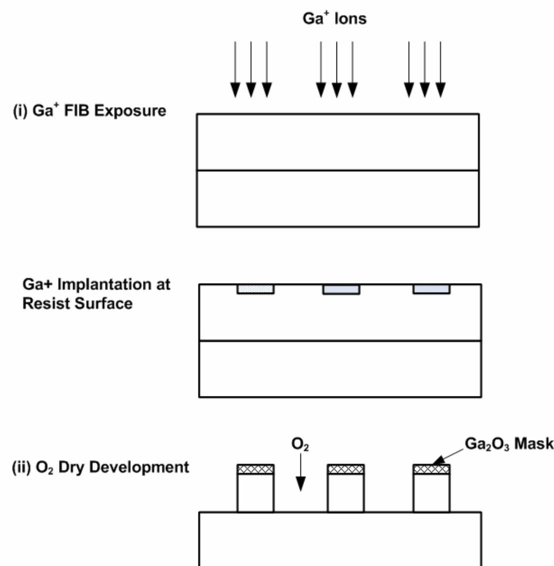

Fig. 1. The 2-step NERIME process diagram, showing (i) Ga^+ FIB exposure step and (ii) oxygen plasma etch develop step.

2. Aspect ratio improvements

Previously reported work has demonstrated the 2-step NERIME process using 1.5μm thick films of the DNQ/novolak based resist SPR660, reporting 100nm CDs with aspect ratios of approximately 15:1 [8]. We show a significant improvement in aspect ratio performance of the 2-step NERIME process, yielding typical aspect ratios of 20:1 using 1.89μm thick films of the DNQ/novolak based resist OIR-89 on silicon substrates, while retaining resist profile control at 90nm CDs.

Through a series of process experiments, we optimised OIR-89 film thickness, Ga^+ ion beam dose and O_2 plasma etch parameters. A 1.89μm thick OIR-89 resist film was exposed with a Ga^+ beam dose of $1.15\text{x}10^{-2}$ C/cm^2, and then dry developed for 1350s in an O_2 plasma etch at 2mTorr pressure. Fig. 2 shows a SEM micrograph of a resultant isolated 90nm resist line, with an aspect ratio of 20:1, formed using this optimised 2-step NERIME process.

Fig. 2 shows a well-resolved resist feature with smooth sidewalls and no visible line edge roughness, a significant parameter in other TSI process schemes. The improvements in resist aspect ratio reported here are particularly significant for subsequent dry plasma etch process steps, where thicker resist layers are usually required to facilitate poor plasma etch selectivity to resist.

Fig. 2. SEM micrograph of 90nm isolated resist line, with 20:1 aspect ratio, formed in 1.89μm thick OIR-89 resist using the 2-step NERIME process.

3. Imaging on various substrate materials

All previously reported work using the 2-step NERIME process used resist patterned on silicon substrates [6]-[11]. The ability to pattern resist on different substrate materials is an important part of integrating any lithography scheme into a process module.

To make the 2-step NERIME process potentially useful in nanolithography applications, it must yield acceptable CD, profile and aspect ratio results on a variety of materials commonly used in device fabrication processes. In this work we demonstrate the 2-step NERIME process on such typical fabrication substrate materials such as polycrystalline silicon (polysilicon), titanium metal (Ti) and CVD silicon dioxide (oxide).

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3.1. OIR-89 resist on doped polysilicon

We deposited 1.89μm thick films of OIR-89 resist on 3000A thick films of N^+ doped polysilicon. The FIB exposure dose and oxygen plasma dry develop steps were optimised through process experiments. The wafer samples received an optimised process with a Ga^+ beam exposure dose of 1.05×10^{-2} C/cm^2, and a dry develop process of 1300s in an O_2 plasma etch at 1.8mTorr pressure. Fig. 3 and Fig. 4 show FIB images of the resultant resist features with 120nm and 250nm CDs, respectively. The images show well resolved resist features, with excellent profile control.

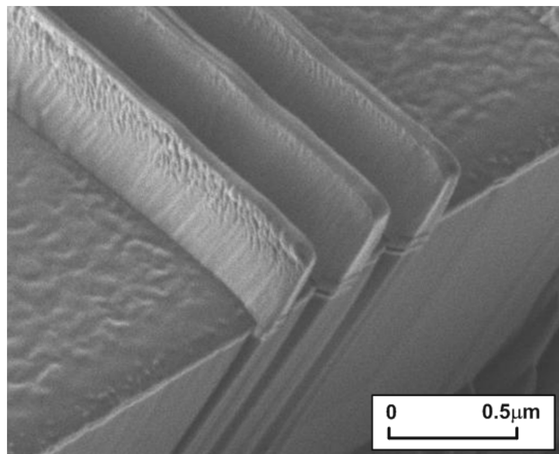

Fig. 3. FIB micrograph, tilted view, of 120nm resist features, with 16:1 aspect ratio, formed in 1.89μm thick OIR-89 resist on 3000A thick film of N+ doped polysilicon using the 2-step NERIME process.

3.2 OIR-89 resist on Ti

We deposited 1.89μm thick films of OIR-89 resist on 1200A thick films of Ti. Again, we optimised the FIB exposure dose and oxygen plasma dry develop steps through process experiments. The wafer samples received an optimised process with a Ga^+ beam exposure dose of 1.25×10^{-2} C/cm^2, and a dry develop process of 1250s in an O_2 plasma etch at 1mTorr pressure. Fig. 5 and Fig. 6 show FIB images of the resultant 90nm resist features. The images show well resolved resist features, with excellent profile control.

The data presented in this section demonstrates the 2-step NERIME TSI process on planar polysilicon and Ti substrates, with 90nm CDs, aspect ratios of 20:1 and excellent profile control.

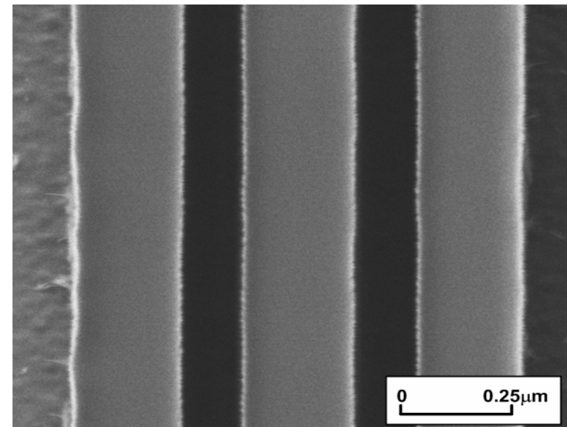

Fig. 4. FIB micrograph, plan view, of 250nm resist features, with 7.5:1 aspect ratio, formed in 1.89μm thick OIR-89 resist on 3000A thick film of N+ doped polysilicon using the 2-step NERIME process.

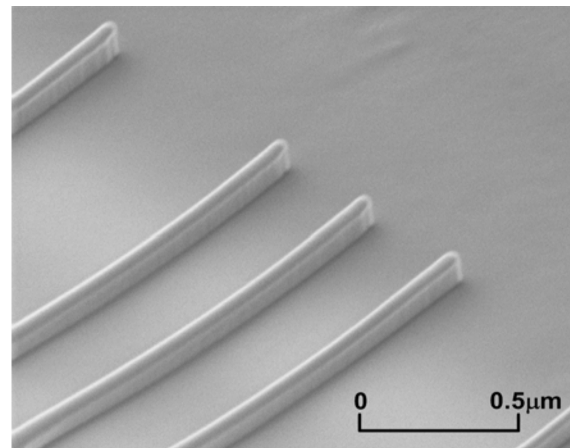

Fig. 5. FIB micrograph, tilted view, of 90nm resist features, with 21:1 aspect ratio, formed in 1.89μm thick OIR-89 resist on 1200A thick Ti film using the 2-step NERIME process.

4. Imaging on topography substrates

To successfully integrate the 2-step NERIME TSI scheme into a useful and practical nanolithography process flow, it must be demonstrated on topography substrates. Resist planarises over topography, and the degree to which this planarisation occurs depends on resist thickness and the height/width of any topography present on the substrate.

Resist planarisation causes localised resist thickness variations that are structure and layout dependant. Resist thickness variations cause imaging

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problems in many lithography processes, making it difficult to control resist CDs and profiles over a range of topography heights. The 2-step NERIME TSI process can overcome poor aspect ratio and unwanted substrate topography effects that affect many other lithographic techniques. We investigated the 2-step NERIME TSI process on topography substrates.

Process experiments were carried out using 1.89μm thick films of OIR-89 and topography wafers with a top surface layer of CVD oxide. The topography present on the substrate wafers caused the resist thickness to vary locally over underlying structures from between 1.5μm to 2.1μm, as shown in Fig. 7. The wafers were exposed with a FIB Ga^+ beam dose of 1.25×10^{-2} C/cm^2, and then dry developed for 1000s in an O_2 plasma etch at 20mTorr pressure. Fig. 8 shows a SEM micrograph of the resultant resist lines formed using the 2-step NERIME process, demonstrating a well-resolved resist pattern over the wafer topography shown in Fig. 7.

Fig. 9 shows a FIB cross-sectional image, taken at 45degree sample tilt, of 90nm resist features patterned in a 1.89um thick film of OIR-89 resist. The image shows the topography present on the wafer, and well-resolved resist features formed over the high and low topography regions present on the wafer.

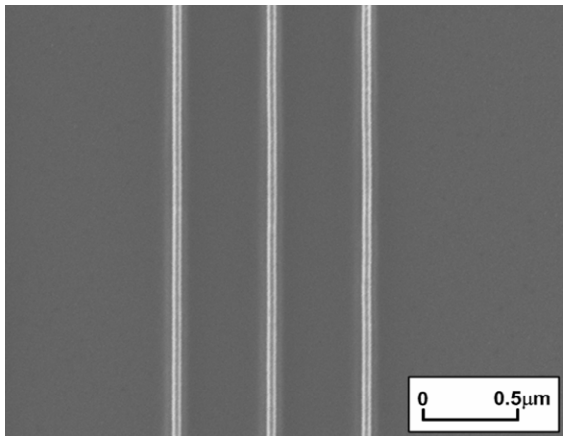

Fig. 6. FIB micrograph, plan view, of three 90nm resist features, with 21:1 aspect ratio, formed in 1.89μm thick OIR-89 resist on 1200A thick film of Ti using the 2-step NERIME process.

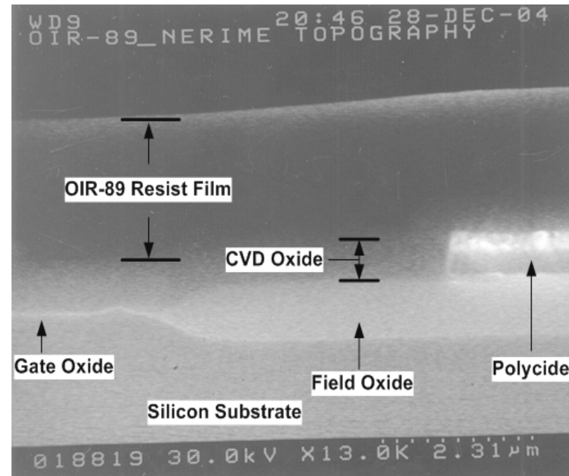

Fig. 7. SEM micrograph showing cross-section through a 1.89μm OIR-89 photoresist layer on topography prior to imaging with the 2-step NERIME process.

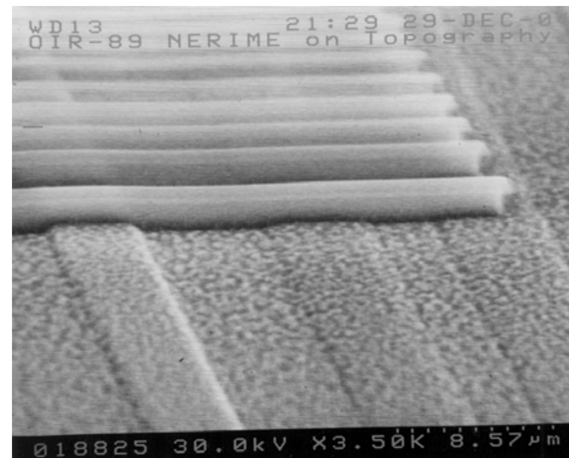

Fig. 8. SEM micrograph of 1.89μm OIR-89 resist features patterned on topography using the 2-step NERIME process.

The data presented in this section demonstrates the 2-step NERIME TSI process on topography substrates, showing fully resolved nanoscale resist features formed on both high and low substrate topography regions of the wafers. The 2-step NERIME process could be further extended to yield sub-50nm CDs. Suitable applications for this optimised process include sensors, NEMs, MEMs, DRAM, CMOS and BiCMOS processing, where high resolution high aspect ratio nanolithography is required over topography.

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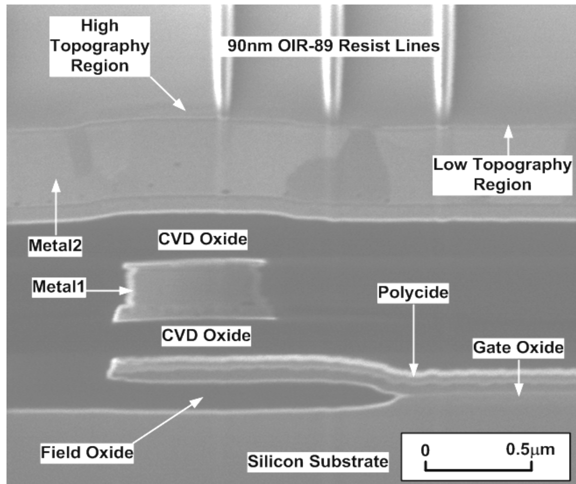

Fig. 9. FIB micrograph of 90nm 1.89μm OIR-89 resist features patterned on topography using the 2-step NERIME process. The image shows resolved 90nm resist structures over high and low topography.

4. Conclusions

We have shown experimentally that the 2-step NERIME TSI process can successfully pattern high aspect ratio nanometer resist features in DNQ/novolak based photoresists. We have demonstrated using the 2-step NERIME TSI process to pattern nanometer resist features on silicon, polysilicon, Ti and oxide substrates, and have also shown that the process can successfully pattern resist features on topography substrates. The improved process performance of the 2-step NERIME TSI process presented in this paper could be further extended to the sub-50nm regime. Suitable applications for this optimised process include MEMs, DRAM, CMOS and BiCMOS processing, or any application where high resolution high aspect ratio nanolithography is required over demanding substrate topography.

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