Silicon Morphology Evolution under Focused Ion Beam Irradiation

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Abstract:

As state-of-the-art lithography techniques approach fundamental limits, interest has increased in alternative nanofabrication methods, including the creation of self-organizing surface topographic morphologies by methods such as ion sputtering. Practical use of this technique requires a thorough quantitative understanding of the morphology evolution and various models have been advanced, but none satisfactorily describes the evolution of all features, especially that of steep slopes (40-90 degrees from horizontal). A recently developed nonlinear model makes novel predictions about the evolution that are partially confirmed by optical profilometry of sputtered surfaces.

Introduction:

The production of novel nano-scale devices and the continuing miniaturization of conventional semiconductors will require new fabrication methods. While lithography in its various forms is rapid, convenient, and well understood, the technique faces several intrinsic limitations and the creation of 3D structures is difficult and time consuming. Thus the possibility of exploiting self-organizing nanostructures for practical fabrication is receiving increased attention. The order in such structures comes from their internal dynamics, meaning that they can exist at almost any length scale. Before any self-organizing structure can be reliably used, however, the process of its creation must be thoroughly understood.

The ripples spontaneously produced by ion sputtering may be a useful class of self-organizing structures. That tiny ripples form on a variety of materials under uniform ion irradiation has long been known [1], however the more recent discoveries that ripple characteristics are a predictable function of irradiation parameters and may be templated by existing structures on the material surface [2] have increased interest in understanding the dynamics of their formation and those of sputtered silicon in general.

The classical theory of sputtering [3] assumes that the energy of each incoming ion is distributed throughout the material in a series of collisions. When energy from these 'collision cascades' reaches the material surface, one or more atoms may be ejected. The rate of this sputtering is determined by the surface shape and material properties. This relationship is well understood for flat and gradually curved surfaces. Our group is developing a new theory [4] that is valid for the steep slopes present in ripples and other self-organizing structures.

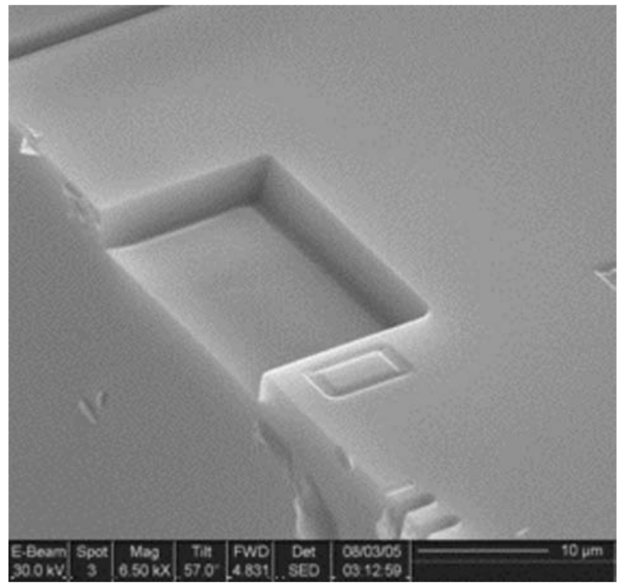

Figure 1: SEM of 80° slope cut into the side of the Si sample.

Using a full nonlinear treatment of the sputtering problem, we identify several behavioral regimes in the evolution of sputtered slopes. Slopes below one critical value (~68°) are expected to gradually dissipate. Above this angle, slopes are expected to sharpen to a dynamically selected angle (~76°). The goal of these experiments was to ascertain the existence and precise values of these angles to check the theory with the simplest possible case: a steep, straight edge.

FIB Machining and Bombardment:

A FEI dual-beam 235 FIB apparatus was used for all sample preparation and imaging steps. The samples were small (< 1 cm^2) chunks of Si <001> wafer. The pattern 'milling' feature of the instrument was used to prepare five identical pits per trial (see Figure 1), normally 25 μm wide, 12 μm long, and 1.7 μm deep, along the cleaved sample edge. The ion beam current was 3nA, while the dwell time and overlap were 1 microsecond and 50%, respectively. The instrument stage was tilted before milling so that the experimental edge was cut at the desired angle. Each pit was then given a 20 x 20 μm high current raster at normal incidence, again using the FIB pattern feature, for either 128, 256, 384, or 512 seconds (see Figure 2).

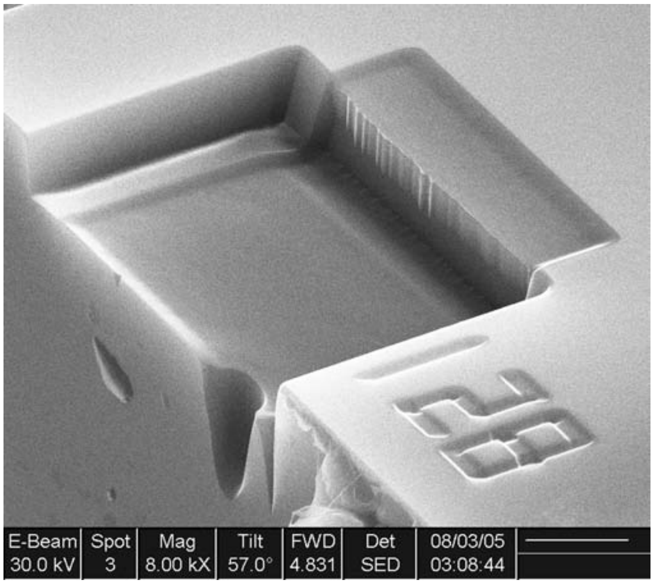

Figure 2: SEM of the 80° slope after 128 seconds of irradiation.

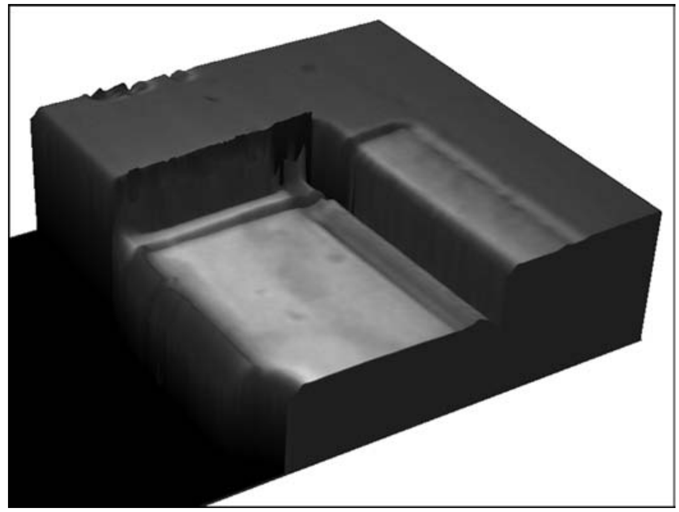

Figure 3: Optically generated profile of pit in Figure 2.

Optical Profilometry:

A hyphenated-systems OP-150 confocal optical profilometer with a 50X objective was used to quantitatively characterize the evolving edges. The maximum slope that the instrument can register in our application is about 45°, so a tilt stage built by H. Bola George was employed to allow complete profiles to be read from the steeper samples. All profiles were converted to averaged 2D line traces drawn perpendicularly to the experimental edge and rotated to the correct position in the plotting software.

Results:

The profilometer is an optical instrument and thus has difficulties analyzing features just two orders of magnitude larger than the wavelength of light; diffractions, reflections, and shadows can all confuse the profiling software. Thus, wholly satisfactory data has still not been obtained and the actual values for the critical angles have not yet been established. Indeed, there are gaps right in the most theoretically interesting regions of the edges. (See Figure 3). We postulate that these gaps occur because shadowing and/or multiple reflections from shock ripples on the evolving edge prevent the profiling software from discerning a clear maximum. Whatever the cause, it is clear that the optically generated profiles (Figure 3) do not yet agree well enough to the SEM images (Figures 1 and 2) for the profiling technique to be considered reliable. Nevertheless, 2D plots of the sequence of edges (Figure 4) do reveal the general evolution of the surface morphology.

Further refinements in the instrument and experimental technique are expected to allow more thorough confirmation of the theory.

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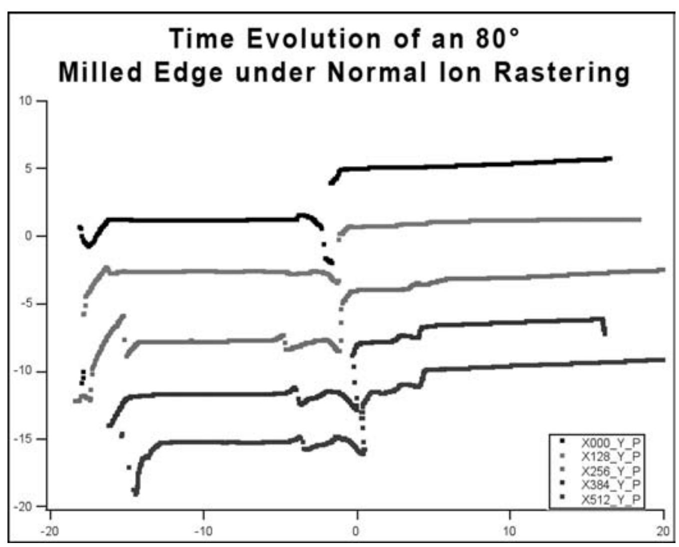

Figure 4: Time evolution of the 80° milled edge under normally incident ion radiation. The traces represent (from top to bottom) 0, 128, 256, 384, and 512 seconds of irradiation.