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Aspects of Beam Control for Single and Dual Beam Systems

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In 1986 the number of FIB systems in use worldwide totaled about 35 [1]. Twenty five years later, it is estimated these systems number in the thousands [2]. From an esoteric research tool to a near-ubiquitous laboratory microscope, FIB equipped systems have evolved and with them so too has the available reference literature [3,4,5] and the associated applications space. A common theme in many of these applications is a trend to more and more complex "patterning" applications (Figures 1 and 2). In many of these applications it is no longer sufficient merely to scan rectangles or trapezoids, but rather users are employing much more complex scan strategies which take advantage of the flexibility of digital scan generator electronics. The heart of a digital scan generator is the digital to analog converter (DAC) itself, with modern scan generator designs typically specified as "16 bit". As microscopists we tend to skip over (or in some cases insist on) this specification without pausing to consider its meaning: a 16 bit scan generator can output 2^{16} (65,536) distinct codes or least significant bits (LSBs). This results in a nominal granularity of about 15 ppm (1/65,536) – a figure, it is perhaps fair to say, that many of us would be skeptical of if it appeared as a measurement of dimensional or concentration precision in a scanning microscope paper we were asked to review. Yet at least from the DAC perspective, many modern 16-bit DACs achieve three-sigma results better than 0.5 LSBs in terms of their differential non-linearity (DNL), a term describing the deviation between two analog values corresponding to adjacent input digital values. Ideally, any two adjacent digital codes correspond to output analog voltages that are exactly one LSB apart. DNL is a measure of the deviation from the ideal 1 LSB step. For example, a DAC with a 1.5 LSB analog output change for a 1 LSB digital code change exhibits 1⁄2 LSB differential non-linearity. An uncorrected DNL greater than 1 LSB will lead to a non-monotonic transfer function in a DAC, which may in turn lead to "reversed" or "missing" lines in a pattern or image. As Figure 3 shows, the devil is in the details even with three-sigma results better than 0.5 LSBs, as mismatch in the "resistor ladder" architecture of most 16-bit DAC integrated circuits can lead to distinct output errors (and thus a few large DNLs), often at codes which are multiples of 2,048 or 4,096. Despite this it is almost certainly true that most of us have greater issues with the temperature stability of our microscope rooms than we do with the DNL of our DACs.

However the realities of microscope electronics, deflection and column dynamics, short and longer term stability for static and dynamic events, overshoot, lag, settling time, scan field anisotropy and beam placement accuracy – all formerly the domain of "exotic" e-beam and i-beam lithography systems and the like, are now becoming important factors to consider as we as microscopists stop merely "milling rectangles" and seek to push the limits of nanoscale beam control from an expert results perspective.

More important still, especially to the novice (or less pedantic) user, are the parameters used to control the beam while patterning. These patterning parameters include the choice of beam current and spot size, dwell time, spacing between consecutive dwells, scanning strategy and algorithms, plus the interaction of the beam with the sample itself, any reactive gas species introduced, and any non-volatilized (re-deposited) material sputtered from the sample during patterning. As Figure 4 illustrates, even for simple shapes milled into single crystal silicon with the same beam, for the same time, the resultant nanomachined topography can be drastically different. More than ever, patterning parameters matter, and the time invested in determining the optimal beam control parameters for a given application is time very well spent.

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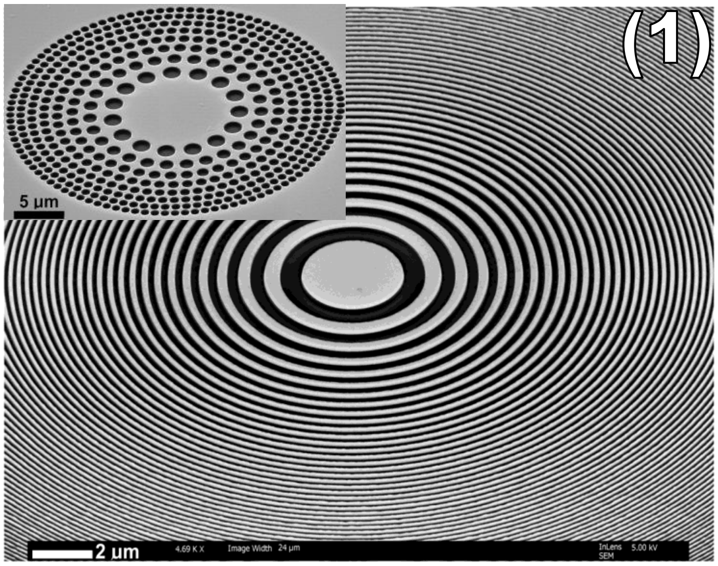

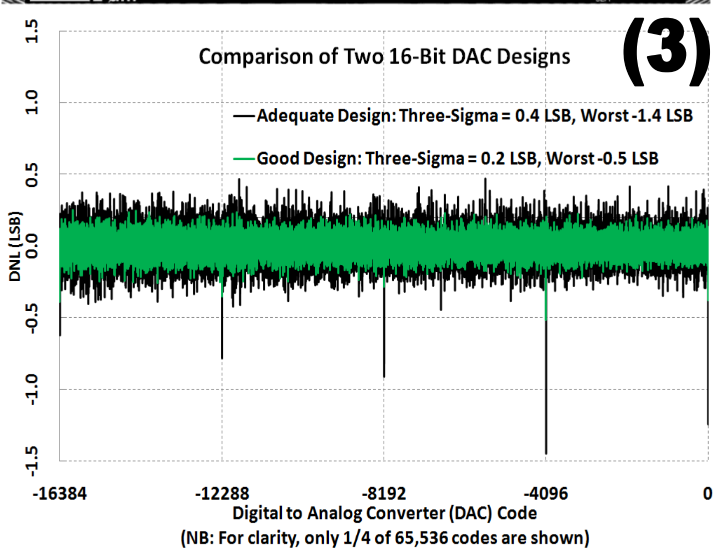

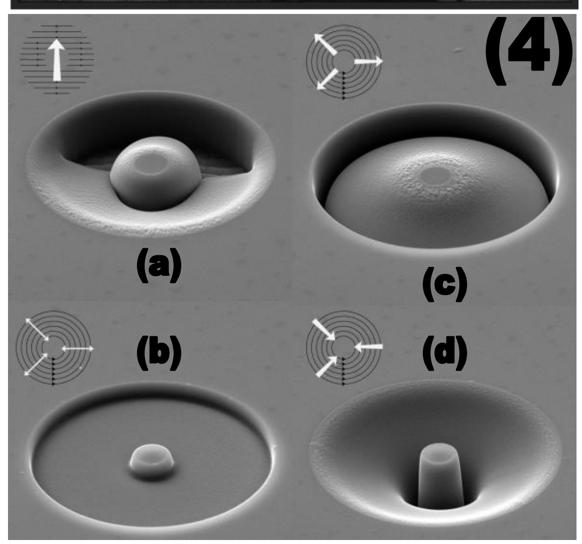

1. Ring and sieve (inset) zone plates, FIB nanomachined into Cr and Au-Pd films on Si and SiO_2 respectively.
2. Top: U.S. National Archives photograph 1634221, used as the source image. Bottom: FIB dose modulated grey-scale rendering (Ga into Si, FIB SE), based on the image at top, after the method described in [6].
3. Comparison of two scan generator designs based on 16 bit DACs. Both designs achieve three-sigma DNL values sufficient to appear monotonic, but one design fails to remain monotonic at codes 0 and -4096.
4. FIB milling of a torus; all conditions (beam current, time on sample, etc.) are identical except scan strategy. (a) Scanning "bottom to top", single pass. (b) Scanning "back and forth", multiple passes. (c) Scanning "inside to outside", single pass. (d) Scanning "outside to inside", single pass.

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