Real-time Dose Control for Electron-Beam Lithography

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Pixel-to-pixel, or shot-to-shot, dose variation during electron-beam lithography (EBL) is a significant practical and fundamental problem. Dose variation arises from both system imperfections[1] and from the random distribution of electron arrival and resist interaction events (shot noise).[2-5] These issues limit the critical dimension control, line-edge roughness, and throughput of EBL. Here we describe the first steps toward providing real-time feedback control of dose for each exposed pixel based on a signal from the *sample to be patterned*, rather than from the source[6-8] or another point in the column.[9-11] As a result, this new technique may ultimately overcome the shot-noise limit.

Fig. 1 (a) illustrates a real time dose control system in which the primary electrons pass through a scintillating material on the sample and produce an optical signal. Under appropriate conditions, the scintillating material produces many photons for each primary electron. The feedback control system detects the optical signal and blanks the electron-beam when a sufficient dose has accumulated in the pixel. In the experiments reported here the optical signal is integrated until the desired dose is reached. This permits correction for most sources of dose fluctuation, but not for shot noise. With sufficiently fast optoelectronics, individual optical pulses corresponding to single electron arrivals could be counted and the feedback system could compensate for shot noise as well.

Fig. 1 (b) shows a block diagram of the feedback control system as implemented on a Raith e_LiNE EBL tool. An elliptical mirror focuses light from the scintillator onto a photomultiplier tube (PMT). A FPGA accumulates the PMT signal during exposure and compares it to a preset threshold value to achieve the desired dose. Fig. 2 plots the beam blanker control signal from the EBL tool and the PMT signal from the scintillator during single pixel exposures with dwell times intentionally set higher and lower than the target dose. When the programmed dose was too high, the feedback system terminated the exposure early, and when the dose was too low the system extended the exposure as required. In a second experiment, we intentionally introduced a random dose variation of 189 fC (1σ) around a mean dose of 629 fC for 53 exposed pixels. In this case, the feedback system increases or decreases the dwell time as needed to control the dose. Fig. 3 shows histograms of the dwell times with and without feedback control.

Thus, we have demonstrated dose control by detecting electron arrivals at the sample itself, rather than by measuring emission current or the current at an intervening aperture in the column. Although in its early stages, such an approach can correct for many sources of dose variation and may ultimately overcome the shot noise limit.

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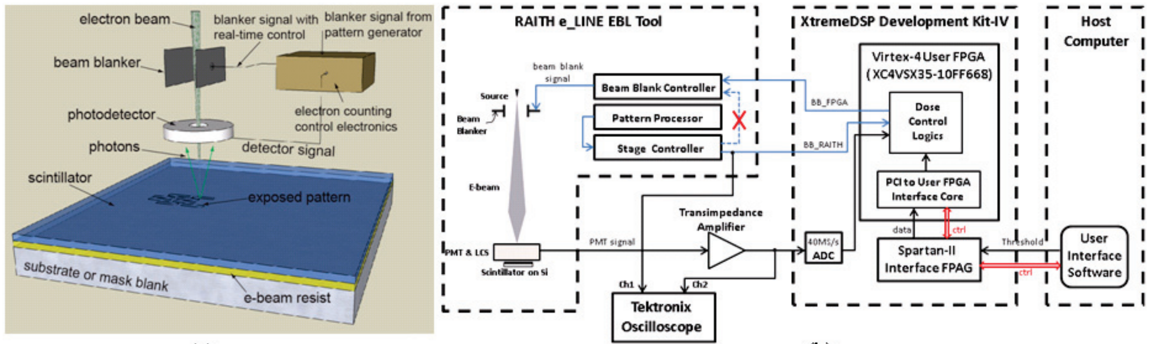
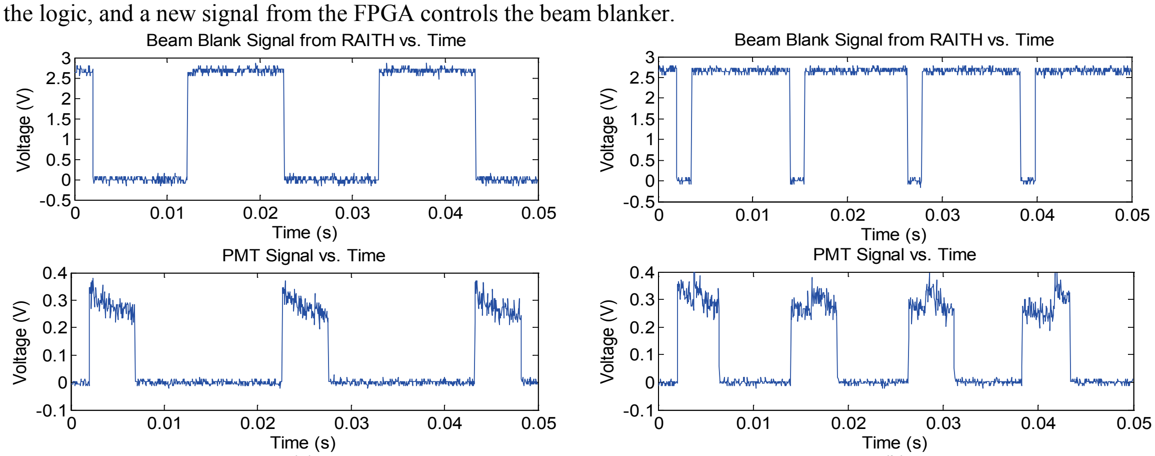


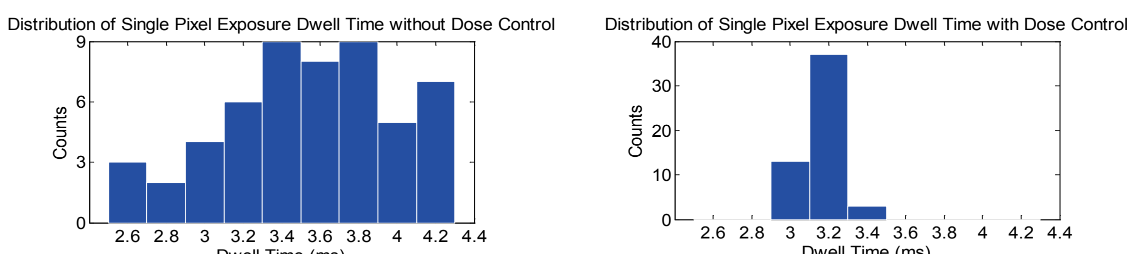
(a) (b)

Figure 1. (a) Illustration of feedback system for real-time dose control. The substrate to be patterned is coated with a scintillating material (p-terphenyl and POPOP in a polyvinyl toluene matrix) that produces an optical signal. The signal is detected and processed to determine when each pixel has received sufficent dose so that the control system can stop the exposure. The optical signal can either be integrated (experiments reported here) to compensate for dose fluctuations characteristic of the system or the individual optical pulses can be counted (equivalent to counting electron arrivals) to compensate for shot noise. (b) Schematic of the experimental setup. A custom light collection system (LCS) containing an elliptical mirror and PMT is introduced into a Raith e_LiNE EBL tool. The signal from the PMT is routed through a transimpedance amplier and an ADC and finally processed by a Virtex 4 FPGA. The beam blanking control signal from the EBL system (original connection shown with "X") now provides the control signal for the logic, and a new signal from the FPGA controls the beam blanker.



(a) (b)

Figure 2. Comparison of EBL system beam blanker signal (upper traces) with scintillator signal from the PMT (lower traces). A voltage of 0 indicates that the beam would be on in the absence of feedback control. All exposures were conducted at 10keV. (a) The dwell time was set to 10ms (nominal dose 2095 fC) and the feedback system achieved the required dose (629 fC) by terminating the exposure early. (b) The dwell time was set to 1.5ms (nominal dose 314 fC) and the feedback system extended the dwell times to achieve the desired dose.



(a) (b)

Figure 3. Histograms of measured dwell times of single pixel expsures (a) without dose control and (b) with dose control. The dramatic reduction in dwell time variance with dose control is apparent. Note, the dwell time variation in (a) was intentionally introduced for illustrative purposes, and is not characteristic of the EBL system.