APPLICATIONS IN MICROSCOPY AND LITHOGRAPHY FOR A HERALDED ELECTRON SOURCE

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ABSTRACT

We describe the design for a heralded electron source made from a standard electron gun, a weak photonic coupler, an electron energy filter, and a single photon detector. We define a figure of merit for the heralding efficiency which describes the sub-Poissonian statistics of the source and can be written in terms of the traditional Klyshko heralding efficiency. Using this figure of merit, we discuss the engineering requirements for efficient heralding. Finally, we discuss potential applications: dose reduction in quantitative bright field STEM and error reduction in electron lithography.

KEYWORDS

Electron gun, electron microscope, electron lithography

INTRODUCTION

Interactions between free electrons and photonic structures have been proposed for non-destructive beam diagnostics [1], beam shaping [2,3], or generating exotic entangled states [4,5,6,7]. While interaction strengths are typically small (≪1 photon per electron), it is possible to repeatedly generate particular states with post-selection. We propose a high-efficiency heralded electron source using an electron energy filter to remove zero-loss electrons as shown in Fig. 1. The heralding efficiency will depend on the overlap between the one-photon and zero-loss energy peaks, so the energy spread of the electron gun should be less than the energy of an optical photon. Just as heralded single photon sources are elementary resources in quantum optics, we anticipate heralded electron sources will be vital for future quantum applications of vacuum electronics. In this extended abstract, we will focus our discussion on immediate applications for heralded electron sources in classical electron-optical systems.

In the next section, we will describe the statistics of a heralded electron source. Then we will analyze two possible applications. In quantitative bright field STEM a heralded source could reduce the dose by an order of magnitude or more. For electron lithograph, heralding could be used to dynamically control the trade-off between write speed and shot noise.

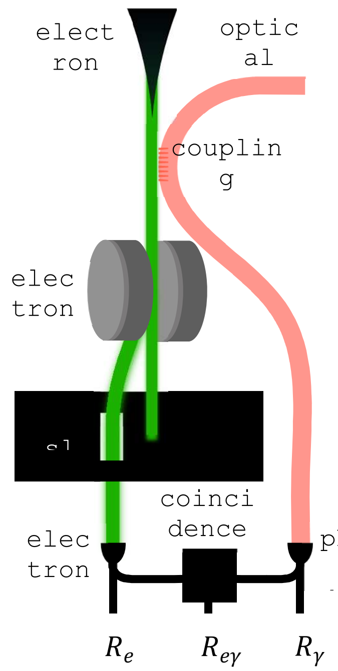

Figure 1: Schematic for a heralded electron source. Electrons produced by the electron gun interact with the vacuum state of an optical waveguide. Electrons which create single photon excitations in the waveguide pass through an energy filter consisting of a prism and slit. The Klyshko electron heralding efficiency depends on the rate of correlated counts $R_{e\gamma}$ relative to the rate of photon counts R_γ.

FRACTIONAL REDUCTION IN VARIANCE

The traditional figure of merit for a heralded photon source is the Klyshko efficiency, which compares the rate of coincident counts in signal and idler channels to the idler channel count rate [8]. With respect to the detector count rates defined in Fig. 1, the Klyshko heralding efficiencies for electrons and photons are defined, respectively, as

$$\kappa_e = \frac{R_{e\gamma}}{R_\gamma}, \text{ and } \kappa_\gamma = \frac{R_{e\gamma}}{R_e} \quad (1).$$

As a figure of merit for electron heralding in the applications we will discuss, the Klyshko efficiency is insufficient as it is insensitive to false negatives (unheralded signal counts). Instead, the electron heralding efficiency can be evaluated using the fractional reduction in electron number variance (FRV), defined as

$$\text{FRV} = \frac{Var(N_e) - Var(N_e|N_\gamma)}{Var(N_e)} \quad (2),$$

where $Var(N_e)$ and $Var(N_e|N_\gamma)$ are the electron number variances without and with heralding, respectively. Assuming the electron and photon detectors have sufficient timing resolution to treat N_e and N_γ for each time bin as a Bernoulli (binary) random variable, we find

$$FRV = \kappa_e \kappa_\gamma \quad (3).$$

To estimate the FRV for the heralding system shown in Fig. 1, we will assume that a fraction $c \ll 1$ of the electrons which pass the coupler emit a photon (and that a negligible fraction emit two photons). The electron prism and slit together form an energy filter which passes fraction f_1 of the heralded electrons and a fraction f_0 of the zero-loss electrons. The total fraction of electrons passing the filter is $f = f_1 c + f_0(1-c)$. Given photon detector efficiency η and background count rate Γ_{bg}, and electron production rate Γ_e, the Klyshko efficiencies are

$$\kappa_e = \frac{c\eta f_1}{c\eta + \Gamma_{bg}/\Gamma_e}, \qquad \text{and} \quad \kappa_\gamma = \frac{c\eta f_1}{f} \quad (4).$$

If the photon energy is much larger than the intrinsic energy spread of the electron beam, then it is possible to have an efficient filter with $f \sim c$ and $f_1 \sim 1$. Assuming the photon background count rate is small compared to the signal rate (i.e., $\Gamma_{bg} \ll c\eta\Gamma_e \sim$60MHz for a 1nA beam and $c = .01$), we can write FRV $\approx \eta$. The best single photon detectors operate in cryogenic conditions and have detection efficiencies of more than 90% (e.g., a superconducting nanowire detector [9]). However, even non-cryogenic single photon detectors can have near-unity detection efficiency [10]. We therefore expect that electron heralding using a photonic coupler could achieve

PARAMETER ESTIMATION IN ELECTRON MICROSCOPY

Quantitative scattering contrast in brightfield scanning transmission electron microscopy (STEM) can be modeled as a parameter estimation problem. For a Poissonian electron source, the sample transmissivity T can be determined by estimating the mean number of electrons reaching the detector. The expected variance in the estimate is equal to the number of electrons expected to arrive at the detector in measurement time Δt: $Var(N_e) = \langle N_e \rangle \propto \Delta t T$. With an efficient heralding system, the detection of a photon initiates a Bernoulli random trial: an electron is detected with probability T. After integrating for a time Δt, the probability distribution for N_e is binomial and has variance $Var(N_e) \propto \Delta t T(1-T)$. The variance with and without heralding is similar when $T \ll 1$, but can differ substantially when $T \sim 1$. As a result, it is possible to dramatically reduce the dose required to estimate T for highly transmissive samples using a heralded electron source.

Fig. 2 shows the dose reduction factor achieved with a high-efficiency heralded electron source. For a sample with mean free path 200nm and thickness t=20nm (T=0.9), the information contained in the heralding counts collected at the photon detector reduces the error (standard deviation) in an estimate of t by a factor of 3 at constant dose or, equivalently, reduce the dose required to reach a threshold measurement error by a factor of 10.

A similar analysis can be applied to scanning electron microscopy (SEM) using a secondary or backscatter electron detector which has probability T of registering a count for each primary electron. A heralded electron source is particularly advantageous when the detector is near saturation (T~1).

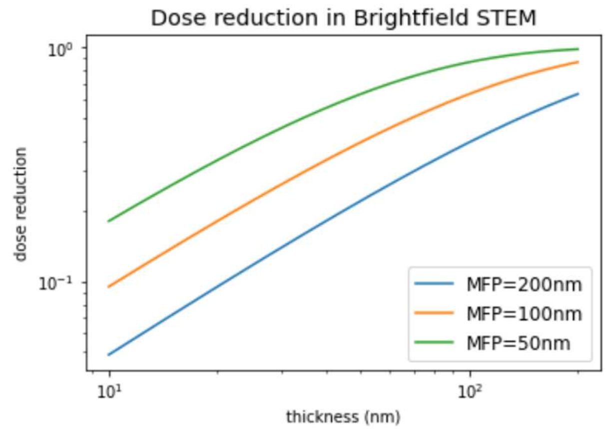

Figure 2: Achievable dose-reduction for brightfield STEM estimates of sample thickness using an efficient heralded electron source for samples of various sample thicknesses and mean free paths (MFP).

REDUCING SHOT NOISE IN ELECTRON LITHOGRAPHY

In electron lithography (EL), Poissonian fluctuations in the beam current can cause errors in the written pattern [11]. For a resist which requires a dose (charge per area) D for exposure, the expected dose error for a pixel of area A is $\sqrt{DA}$. The error can be reduced by using larger pixels (reducing resolution) or choosing a less sensitive resist. However, low sensitivity resists require long write times.

For a beam current density J and clock speed S, the maximum write speed is achieved when the exposure dose is $D < JS$. For $D > JS$, the writing speed becomes current-limited. As an example, suppose J =100 A/cm^2 and S=100MHz. Then the maximum write speed is possible for resists with D <1uC/cm^2 or 6 electrons per (10nm)^2. To get less than 10% dose error in each (10nm)^2 pixel, the resist sensitivity would need to be decreased so that $D > 100$ electrons per pixel, slowing write speed by a factor of 16. To achieve less than 10% error using (4nm)^2 pixels, the write speed would need to be 100 times slower than the maximum (clock) speed.

To use heralding for more accurate dosing, the exposure is divided into m stages and the dose applied at each stage is chosen based on the number of remaining stages and the dose applied so far (based on the number of detected photons). In Fig. 3, we choose the target dose D_k at stage k according to

$$D_k = f(D - \sum_{k'<k} D'_k) \quad (5),$$

where D is the total target dose and f is between 0 and 1.

The optimal choice for f depends on D and m. In Fig. 3, we optimize f to the within 10% to minimize the (root mean square) dose error.

Heralding according to the scheme shown in Fig. 1 entails a significant reduction in beam current. However, it enables dynamic control the trade-off between speed and noise. Using a single layer of resist, heralded electron lithography could quickly expose regions of low detail, then apply a low-noise multi-stage exposure to areas where noise could limit device yield. In order to more fully understand the potential value of a heralded source for electron lithograph, it will be necessary to develop a more detailed model of the various stochastic elements of the exposure process.

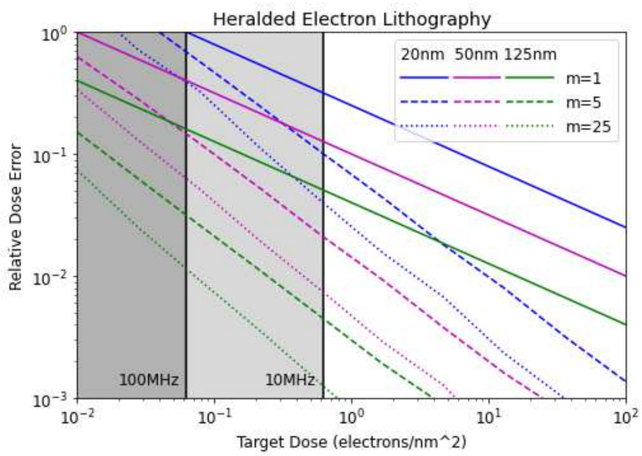

Figure 3: Relative dose error (standard deviation per mean dose) vs exposure dose for three different line widths (with 5 pixels per line) using a 100A/cm² electron source. The error can be decreased by increasing line width or by using less sensitive resist. To the right of the grey regions, write times are limited by beam current rather than clock speed. Write speed can be increased at constant line width using a heralded electron source and m>1 stages.

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