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Electron optics for dual-beam low energy electron microscopy

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ABSTRACT

Dual-beam low energy electron microscopy (LEEM) is a novel imaging technique that extends LEEM applications to non-conductive substrates. In dual-beam LEEM, two flood beams with opposite charging characteristics illuminate the field of view in order to mitigate the charging effects occurring when substrates with insulating or floating surfaces are imaged in a LEEM. The negative charging effect, created by a partially absorbed mirror beam, is compensated by the positive charging effect of either a higher energy electron beam with an electron yield exceeding 1, or a photon beam. The electron-optical designs of existing and novel dual-beam LEEM approaches are reviewed and compared.

1. Introduction

Low energy electron microscopy (LEEM) is a powerful parallel imaging technique [1] that typically utilizes electron landing energies from 0 to a few tens of eV. LEEM provides information about the topmost atomic layer, and is thus ideally suited for the characterization of surface properties. However, when a conventional LEEM instrument is used to image insulating specimens, the low landing energy exacerbates charging effects resulting in significantly reduced image quality. On a homogeneous insulator surface, the charging can be suppressed by operating at a landing energy resulting in a net electron yield of 1. However, this approach restricts the landing energy and typically does not work when different insulating materials are present on the surface.

The dual-beam approach, originally proposed in the early 1990s by L.H. Veneklasen and experimentally demonstrated at KLA-Tencor [2], is a practical solution to this problem. In a dual-beam LEEM, two electron beams with different landing energies or a photon and electron beam are used to mitigate the charging effect (see Fig. 1). When an insulating substrate is illuminated with a low energy electron beam with landing energy near 0 eV, a fraction of electrons is mirrored and the remainder is absorbed, charging the surface negatively. When a higher energy electron beam ($\sim$100 eV or more) is used, secondary electrons are emitted and the electron yield can exceed 1, charging the surface positively. In the photoemission mode, where UV photons are used to illuminate the specimen, the surface always charges positively as electrons are emitted. However, when two beams with opposite charging characteristics, i.e. a mirror electron beam and either a higher energy electron beam or UV photon beam, are superimposed on the substrate, charging effects can be neutralized.

2. Dual-beam LEEM approaches

Multiple electron-optical implementations of a LEEM with dual beam illumination have been proposed and developed [2–5].

2.1. Electron–photon illumination

The combined electron–photon illumination can be readily achieved in a LEEM instrument equipped with a UV light source [2], as shown in Fig. 2. The charging effect is mitigated by the combined charging effects of the overlapping mirror electron and UV light beam. The electron beam is partially mirrored and its high energy tail is absorbed, which charges the surface negatively. For a UV light beam with photon wavelength short enough to release photoelectrons, the photoemission yield $\gamma>0$ (nA/mW) and the surface charges positively. If the portion of the mirror beam current I_m that is absorbed equals to αI_m, and the photoemission current equals to I_λ, the condition for charge equilibrium then can be written as

$$\alpha I_m = I_\lambda = \gamma P \tag{1}$$

where P is the laser power needed to generate the required photoemission current I_λ. The verification of the dual electron–photon approach was demonstrated experimentally in Ref. [2].

However, the photoemission yield γ of most specimens is low, and conventional broad-band UV sources are not bright enough to neutralize the relatively large mirror beam current. Continuous-wave, high-power deep-UV lasers are needed to achieve useful imaging conditions. Thus the dual electron beam approach is much more suitable for practical imaging applications.

2.2. Dual electron-beam illumination

In the dual electron-beam approach, the charging effect is mitigated by the combined charging effects of the overlapping

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mirror and higher energy electron beams. The first beam is partially mirrored and its high energy tail is absorbed, which charges the surface negatively. The second beam, frequently referred to as the "charge control beam", strikes the wafer with energies of typically few hundred eV, results in a total (secondary and backscattered) yield σ larger than 1 that charges the surface positively. If the portion of the mirror beam current I_m that is absorbed equals to αI_m, and the high energy charge control beam current is I_{cc}, the condition for charge equilibrium then can be written as

$$\alpha I_m = (\sigma - 1) I_{cc}. \quad (2)$$

The challenge is to design an electron optical system that can deliver overlapping illumination of the mirror and charge control beams at preferably normal incidence on the substrate, i.e. a system that combines two parallel electron beams with different energies

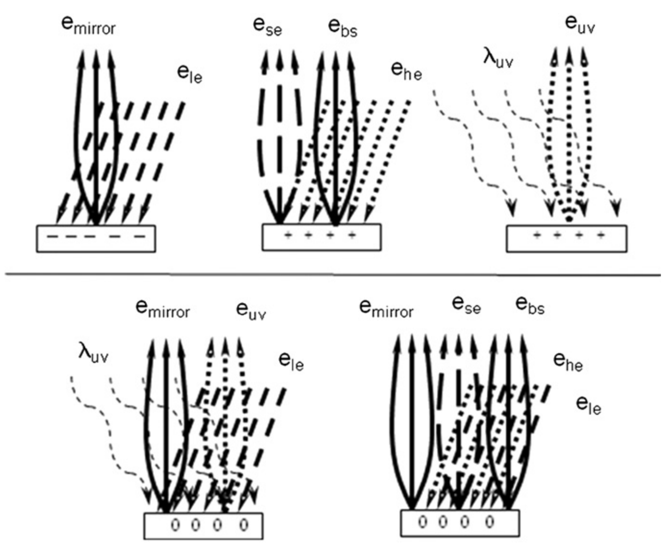

Fig. 1. Surface charging with single beam (top row): left—mirror electron beam, center—few 100 eV electron beam, right—UV photon beam; and charge balance under dual beam illumination (bottom row): left—mirror electron beam and UV photon beam, right—two electron beams with low ($\sim$0 eV) and high (> 100 eV) landing energy; e_{le} - low energy electrons with landing energy near 0eV, e_{mirror} - mirrored electrons, e_{he} - high energy electrons with landing energy of a few 100eV, e_{se} - secondary electrons, e_{bs} - backscattered electrons, λ_{uv} - UV photons, e_{uv} - photoemitted electrons.

and currents at the substrate surface. In what follows the electron-optical design of existing and novel dual-beam approaches is reviewed and their strong and weak points are compared.

2.2.1. Veneklasen's approach

The original proposal by Veneklasen and Adler [3] utilized the dispersion of the magnetic prism to recombine two electron beams. Fig. 3 shows the basic electron-optical configuration of this dual-beam approach. It includes two electron guns biased at slightly different potentials that each emit a beam of primary electrons along two separate paths. Both electron beams are collimated by their individual zoom lenses and enter the magnetic prism separator inclined at a small angle with respect to each other. The separator bends the collimated electron beams so that they are both incident along the optical axis of the immersion objective lens normal to the specimen surface. The prism separator deflects the higher energy electron beam by a slightly smaller angle than the lower energy mirror electron beam. When the difference between the prism deflection angles equals the inclination angle of the two beams entering the prism separator, both beams coincide on the same specimen location and strike the specimen at normal incidence. After the beams are deflected by the prism into the objective lens, the electrons are decelerated and focused by the objective lens to form parallel flood beams. The incident electrons are scattered by the specimen and form a 2-dimensional image. This image is then refocused by the objective lens and deflected by the prism array into the projection optics, which magnifies the image on a viewing screen.

The practical implementation of this approach is rather difficult, due to the small difference in deflection angles. For a 30 keV electron beam energy and bias differential of 300 V, the difference amounts to only about 5 mrad. This means that the guns must be impractically far from the prism in order to not overlap. In principle, one can increase the angular separation by lowering the beam energy in the prism, however this is not desirable due to increased Coulomb interactions and geometric aberrations. Several electron-optical schemes have been proposed to address this shortcoming, introducing novel components including a dual beam gun and a semitransparent electron mirror.

2.2.2. Dual electron beam gun approach

In the dual electron beam gun design [4], two independent electron beams are generated in an electron gun equipped with two concentric cathodes, with the outer ring cathode biased negatively

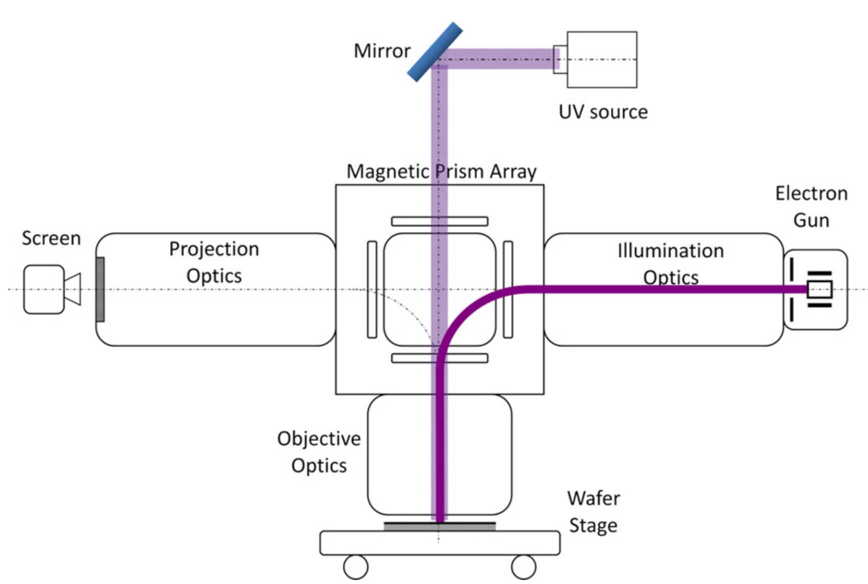

Fig. 2. Electron-optical diagram of a dual photon–electron beam LEEM.