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Experimental results using an improved low-energy focussed ion beam column with booster principle and free-standing target

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ABSTRACT

The design and experimental results achieved with an improved low-energy focussed ion beam (LEFIB) column are presented. The ion optical column is based on booster principle and electrostatic immersion lenses which are operated in the internal acceleration mode. Ion beam retarding is accomplished within the objective lens. Therefore the target is free-standing, i.e. on ground and in a field-free region, and the secondary electrons can easily be detected. The simulated diameters of the high-current gallium ion probe including the important underlying physics of Coulomb interaction have been confirmed in experiment, e.g. 780 nm at 1 keV landing energy, 1 nA beam current and a free working distance of 10 mm.

1. Introduction

The focussed ion beam (FIB) is a very useful tool for diverse applications in micro- and nanotechnology. The effects of the ions on the target, the potential of the FIB technology in general, existing FIB systems (ion sources and optics), and many applications have already been reviewed by Melngailis [1], Orloff [2], and Gierak [3]. Many FIB systems are applied in semiconductor industry for circuit repair (cutting and joining of conductors), photomask repair, circuit inspection, failure analysis, and reverse engineering. The FIB is also used for maskless lithography as well as for patterned implantation of dopants during circuit development. Furthermore, considerable progress has been made in the preparation of site-specific cross-sectional TEM (transmission electron microscopy) specimens using the FIB. Among plenty of additional applications there is direct material deposition for in situ contact formation and generation of patterned thin films, e.g. superconductive or magnetic films.

The performance data of a common commercial FIB instrument with a Ga LMIS (liquid metal ion source) are as follows: resolution = 5–7 nm at 30 keV energy, probe current = 1 pA–50 nA, energy range = 3–30 keV. The ions of this keV range damage the crystal structure of the specimen and hence amorphization occurs. Kato et al. [4] found a 20 nm wide damaged layer after 30 keV FIB milling of crystalline silicon at an angle of incidence of 1.2°. The damaged layer could be somewhat reduced by final polishing with an ion energy of 5 keV. Graff et al. [5] report that the amorphous layer could nearly be removed by using 2 keV gallium ions. But it is known that only for very low energies (≈<200 eV) the ion penetration and the physical sputtering is negligible [6]. Therefore an energy of 200 eV (or 500 eV at most) is necessary for the important FIB application of direct surface deposition.

Already several laboratory low-energy focussed ion beam (LEFIB) systems have been built for landing energies below 1000 eV [7–14]. Most of them [7–10,12,13] retard the positive charged ions between the last lens electrode and the specimen which is on high positive potential (and not on ground). Therefore the electrostatic field at the specimen is very high and the specimen itself is part of the ion optical system. With such a system a very small probe diameter can be achieved if the following disadvantages are accepted: (1) the secondary electrons (SE) are attracted by the specimen and therefore either secondary ions (SI) have to be used for signal detection or the system has to be operated in the mode of scanning transmission ion microscopy (STIM) for taking images. (2) Damage of the specimen can occur by microdischarges. (3) Distortion of the retarding field is possible by the specimen holder, the gas inlet system or – on a more microscopic basis – by the local topography of the specimen itself. This will result in parasitic image aberrations, e.g. low-order distortion.

We briefly report on the performance data already achieved with LEFIB systems in [7–14] before we introduce our system. Narum and Pease [7] measured a resolution of 0.65 μm at 1 keV and 0.95 μm at 25 eV landing energy for a target current of 1 nA Ga ions using the knife edge method for resolution determination. Kasahara et al. [8] detected the SI using a micro-channel plate (MCP) and found a resolution of 200–300 nm for Ga ions with 1 keV landing energy. Aihara et al. [9] used the same ion column as in [8]

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but introduced an additional electrode between the specimen and the MCP. This electrode has the same (high positive) potential as the specimen and reduces the electric field at the specimen. Yanagisawa et al. [10] report on a LEFIB system which is combined with a molecular beam epitaxy (MBE) apparatus. From a STIM image of a Ni grid these authors estimated a probe diameter of 500 nm at 100 eV landing energy and 100 pA ion beam current. This probe diameter is a lot higher than the simulated value of 50 nm and the cause of the discrepancy is not clear. Pak et al. [11] kept the specimen on ground potential but supplied a highly negative bias to the complete ion optical column to retard the positive Ga ions in front of the specimen. The paper does not contain resolution values for the incident energies varied from of 30 eV to 500 eV. Nagamachi et al. [12] deposited gold lines with a width of 8 μm at 30 eV landing energy and a beam current of 40 nA. Using 200 eV landing energy and a beam current of 40 pA the authors measured a line width of 0.5 μm. In both cases the simulated resolution was better than the measured value which may be a result of the neglected Coulomb interaction (CI). Nebiker et al. [13] used a commercial ion optical column from Raith/Orsay Physics in connection with a highly positive bias at the specimen. From STIM images of a Cu grid these authors found resolution values of 3 μm at 40 eV and 1 μm at 200 eV. In [14] an ion optical column with four electrostatic lenses (including the gun lens) is proposed. The schematic illustration is very bewildering because the authors used coil symbols for electrostatic lenses (2nd and 3rd lens) and also for the four individual electrodes of the last lens which serves for "isotropic retarding". It seems that the Ga ions are first accelerated up to 10 keV and subsequently retarded continuously within the 4th lens to a very low energy. The GaAs specimen is at ground and field-free. It appears that the ray path is crossover-free. Lines of Ga droplets are deposited using an ion beam current of 1 nA. These authors observed probe diameters of 5 μm at 100 eV and 10 μm at 30 eV. Some other previous LEFIB systems have already been discussed by Rauscher and Plies [15].

2. Ion optical column

In our LEFIB system whose former version has already been published [16–19] the specimen is on ground potential and in a field-free region as the last electrode of the objective lens is grounded, too. Thus there is only a small penetration of the internal electrostatic lens field through the hole of the last electrode and we use the notation free-standing specimen. Such an ion optical column has the advantage that it can be combined with an electron optical column in a dual beam instrument. Other basic characteristics are:

- Use of immersion lenses (condenser lens and objective lens).
- Operation of the lenses in the internal acceleration mode.
- High ion energy in the drift space (liner tube) between the two lenses, i.e. booster principle.
- Telecentric ray path between the two lenses, i.e. the axial ray bundle is parallel to the optic axis in the drift space.

Due to problems with the limited flashover stability of the former condenser lens we had to operate this lens regrettably in the internal deceleration mode. Therefore the complete gun including the condenser lens was redesigned by Marianowski [20]. In Marianowski's new design the first electrode of the condenser lens is no longer electrically connected with the extraction electrode of the LMIS. This improvement was already proposed by Rauscher [19]. Another disadvantage of our former column was the post-lens scanning deflector, which is now replaced by a double-stage pre-deflection system, see Fig. 1. The impact of CI on the resolution of

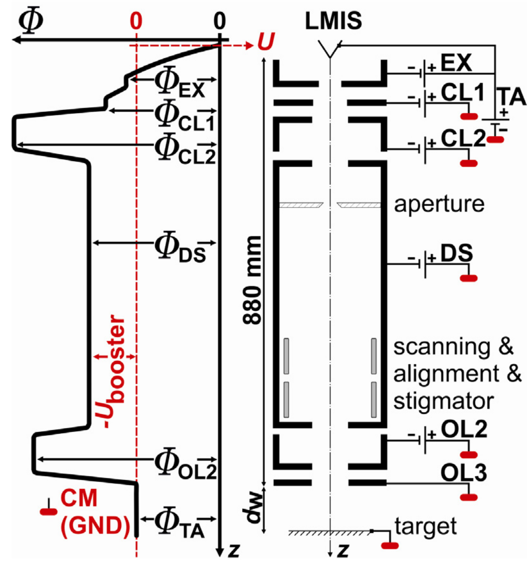

Fig. 1. Schematic distribution of the (kinetic) axial potential Φ and the ground (GND) related voltage U. The signal ground of each power supply is connected to a central mass (CM) plate. The related devices of the highly developed low-energy focussed ion beam system are sketched aside. The potential of the extractor is Φ_{EX}. The condenser lens (CL) consists of three electrodes. The potentials of the first two are Φ_{CL1} and Φ_{CL2}, respectively. The third electrode has the same potential as the drift space Φ_{DS}. The objective lens consists of three electrodes as well. Its first electrode is on drift space (liner tube) potential, the second electrode potential Φ_{OL2} can be controlled individually. The third electrode Φ_{OL3} is on ground ($U = 0$) like the target (TA) itself. Hence the target is (almost) in field-free space. The landing energy of the single charged positive ions emitted from the liquid metal ion source (LMIS) is given by $E = e\Phi_{TA}$. We have to mention that the real axial distribution of $\Phi(z)$ is more smooth than in our schematic graph and the axial value is always less than the boundary value of the neighbor electrode.

a LEFIB column is essential and was already partly considered in the simulations of our former system. But we started a fresh, more rigorous and complete (and therefore very time-consuming) simulation of this effect for our new LEFIB system based on immersion optics. To provide safe results we used two different software packages [21,22]. The simulations [23,24] show that it is most important to realize a high drift space potential and a low working distance. In comparison, the internal acceleration mode operation and the overall column length (and hence the drift space length) are not so important. The last dependence on the drift space length is very important if additional components, e.g. a mass separator, are to be integrated between the two immersion lenses. We should mention that almost all investigations on CI in FIB systems treat systems of two Einzel lenses, see e.g. [25,26], or the CI is simulated in the LMIS (tip to extractor) [27]. Therefore we could not rely on earlier results but had to simulate our new improved LEFIB column right from the beginning.

Fig. 1 shows a schematic potential distribution together with the lens electrodes and the high voltage power supplies. $\Phi(z) = \varphi(0,0,z)$ is the axial kinetic potential which is the kinetic energy divided by the elementary charge e if the positive ion is single charged. $U(z)$ is the ground-related axial potential. The condenser lens resembles the optimized lens by Orloff and Swanson [28], the objective lens has been modified to meet experimental requirements. Not shown is the vacuum isolation valve arranged just above the aperture and electrically connected to the liner tube (drift space). The aperture is also at the same high negative voltage $U = U_{booster} < 0$. In the lower part of the liner tube two electrostatic 8-pole elements are arranged which serve as scanning unit (dynamic voltages) as well as alignment unit (static voltages). Additional static voltages for generating a variable and rotatable quadrupole field to correct an arbitrary two-fold astigmatism of first order are applied to the