A design for a subminiature, low energy scanning electron microscope with atomic resolution

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We describe a type of scanning electron microscope that works by directly imaging the electron field-emission sites on a nanotip. Electrons are extracted from the nanotip through a nanoscale aperture, accelerated in a high electric field, and focused to a spot using a microscale Einzel lens. If the whole microscope (accelerating section and lens) and the focal length are both restricted in size to below 10 μm, then computer simulations show that the effects of aberration are extremely small and it is possible to have a system with approximately unit magnification at electron energies as low as 300 eV. Thus a typical emission site of 1 nm diameter will produce an image of the same size, and an atomic emission site will give a resolution of 0.1–0.2 nm (1–2 Å). Also, because the beam is not allowed to expand beyond 100 nm in diameter, the depth of field is large and the contribution to the beam spot size from chromatic aberrations is less than 0.02 nm (0.2 Å) for 500 eV electrons. Since it is now entirely possible to make stable atomic sized emitters (nanopyramids), it is expected that this instrument will have atomic resolution. Furthermore the brightness of the beam is determined only by the field emission and can be up to 1×10^6 times larger than in a typical (high energy) electron microscope. The advantages of this low energy, bright-beam electron microscope with atomic resolution are described and include the possibility of it being used to rapidly sequence the human genome from a single strand of DNA as well as being able to identify atomic species directly from the elastic scattering of electrons. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3058602]

I. INTRODUCTION

It is fairly well known that the effects of aberrations in lenses[1] are directly proportional to the focal length. This simple fact has limited the ultimate resolution of most large scanning electron microscopes where the focal length of the final lens is a few millimeters to less than around 1 mm. In these instruments the final lens produces a demagnified image of an upstream aperture, which is used to collimate the beam and hence reduce its emittance so that it can be focused to a small spot. Furthermore, diffraction at this collimator may also limit the ultimate resolution, and it is not usually possible to get nanometer resolution unless the energy is in excess of 10 keV. The ultimate brightness of the beam is largely determined by the aberrations throughout the instrument from the extractor/condenser lens onward. Even when the collimation has severely reduced the brightness of the beam, it is still necessary to employ considerable aberration corrections in the final lens. Recent developments[2] in employing adaptive optics for this final lens have meant that beams of energy around 100 keV can now be focused down to around 0.1 nm (1 Å), but the necessity of reducing the emittance (by collimation) means that the final beam current can only be around 10 pA, a thousand times smaller than this new type of microscope.

All of these problems can be largely eliminated by scaling the instrument (and the focal length) down in size by about a factor of 10^5, where it is then possible to image directly the field-emission site(s) of a nanotip even at energies as low as 300 eV. The brightness of the beam is then determined by the field emission and can be up to a factor 10^6 times greater than a conventional instrument even at these low energies. Furthermore it is not necessary (or desirable) to collimate the beam since this can degrade the resolution by diffraction, and charging of insulators and electrode (insulating) surface layers can result in steering and defocusing effects.

II. DISCUSSION

The principle of the design is shown in Fig. 1(a), where the electron beam from the field emission from a nanotip is first accelerated in a high field, generated by applying a negative voltage V_A to the first electrode and then focused to a spot using a single Einzel lens. The electrons are extracted from the nanotip by applying a voltage V_T to the tip and are immediately accelerated in a gap of length typical 1–2 μm. These electrons can be then be focused down to a spot, in a distance which is typically around 6 μm, without putting excessive electrical stress on the insulators. In this design the maximum beam diameter d is around 100 nm (typically 1/4 of this for an atomic emitter) so that the increase in the beam spot sizes from chromatic aberration, $(\Delta E/E)d$, for a nano-

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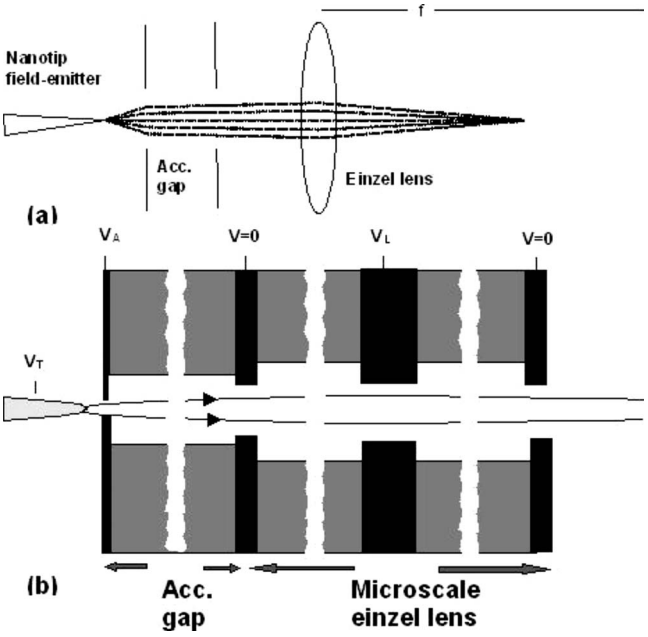

FIG. 1. Schematic of the microscope showing how it directly images the field-emission site(s) on a nanotip. The overall length of the instrument is less than 10 μm and the aperture is typically 0.5 μm.

meter and an atomic emission site, respectively, are 0.02 and 0.05 nm (0.2 and 0.5 Å) for a beam energy E of 500 eV and a spread in energy ΔE of 100 meV. (This difference in spot sizes is because the beam size d is smaller for the point size emitter.) This is smaller than the diffraction limit of $\lambda/2 = 0.05$ nm (0.5 Å).

A practical embodiment of this microscope is shown in Fig. 1(b). It is a simple multilayer construction of metal electrodes and insulator material (silica or alumina) with a hole "drilled" in it and a nanotip positioned centrally over the hole in the "extraction" aperture, which has diameter of greater than 30 nm. Electrons, which are extracted from the nanotip, are accelerated in the next section to an energy eV_T. Typically V_A might be in the range from -300 to -500 V and $V_T - V_A$ in the range from +2 to -30 V. If the insulator is around 1 μm, then the field is comfortably below the breakdown strength of alumina or silica. (This can be increased to 1.5 μm without much loss of performance.) An Einzel lens with a 500 nm aperture directly follows this accelerating section and focuses the beam at distances around 5 μm from the end of the lens.

The performance of the instrument has been studied by numerical simulations using the ray tracing program SIMION. This type of calculation reproduces a Gaussian beam[3] and is exact unless the beam is collimated where diffraction must then be considered so that the propagating beam in the system must then be computed with the Fresnel–Kirchoff integral.[3] In this microscope the beam is always very much smaller than the aperture in the microscope, so the diffraction limit is determined solely by the electron wavelength. The starting point of the rays is the phase space at the tungsten nanotip, which has a radius of 5 nm, which was approximated by a rectangle of eight points on the periphery (as defined by the full width of the Gaussian beam) of the occupied phase space with the size of the emitting area being 1

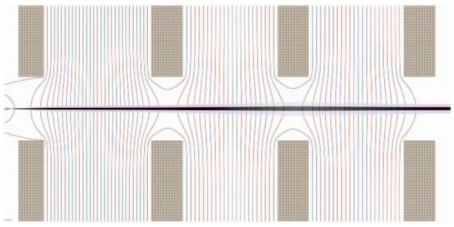

FIG. 2. (Color) The envelope of the electron trajectories for a point source (black) and a 1 nm source (blue) for a microscope with a uniform 500 nm aperture. The tip voltage V_T is -515 V, the accelerating voltage V_L is -500 V, and the Einzel lens is at a voltage $V_L = -380$ V. The beam is focused to a spot of 0.04 nm (4 Å) for the point source and 1.24 nm (12.4 Å) for the nanometer source at a distance of 4.9 μm from the end of the microscope.

$\times 1$ nm and the full angle of emission being 6°, a figure extrapolated from measurements[4–7] on supertips. This empirical figure therefore includes space charge effects, which are, however, negligible at beam currents of nanoamperes. The emission energy was assumed to be 4 eV.

Figure 2 shows the beam profile defined by these rays for a point source and a nanometer sized emitter, positioned 60 nm from the first aperture, for a beam energy of 515 eV ($V_T = -515$ V) with $V_A = -500$ V and $V_L = -380$ V. These produce beam spots of 0.04 nm (0.4 Å), full width at half maximum, and 1.24 nm (12.4 Å) at a distance of 4.9 μm from the end of the microscope. The beam spot size can be reduced by increasing the voltage on the Einzel lens so that at around 4 μm from the end the beam, spot sizes are 0.03 nm (3 Å) and 0.9 nm (9 Å), respectively. This is the approximate position of unit magnification, and it is not necessary, or desirable, to increase the distance between the Einzel lens and the accelerator section so as to obtain demagnification. The ray traces for the point sized emitter show that presently, the aberrations are much smaller than the calculated diffraction limit of 0.05 nm (0.5 Å). (Note that the aberrations can only be obtained from the ray trace plots.)

The performance of the instrument is therefore limited by the size of the electron emission site, and since the manufacture of stable atomic sized electron emitters[4–7] (nanopyramids) is now becoming routine, it is clear that this microscope will have a resolution of the order of 0.2 nm (2 Å). However, what is important is that the microscope is matched to the electron emission site since the size of this will vary according to the applied field. Thus atomic emitters (nanopyramids) are stable up to 10 nA of current at applied fields much lower than that for typical nanotips. This lower field can be achieved by reducing the voltage on the tip and/or moving the tip farther from the entrance aperture. Figure 3 shows the field at a nanotip of radius 5 nm for varying voltages V_T at a distance of 30 nm and for a fixed Einzel lens voltage of -380 V. In all cases the position of the focus can be varied with subsequent change in the beam spot size with the unit magnification point being at around 4 μm from the end of the Einzel lens where $u/v \approx 1$. It is also possible to adjust the tip field by changing the nanotip radius on which the atomic emitter is built. In fact it is desirable to have a fairly large nanotip radius, 100 nm, for example, because the angle of emission reduces considerably when the

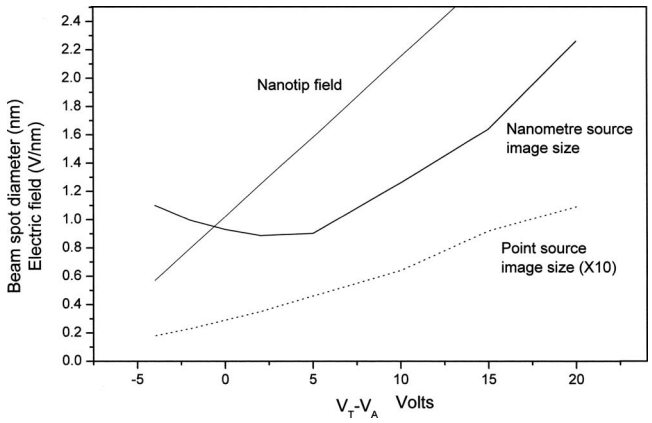

FIG. 3. The beam spot size and the electric field strength on a nanotip of 5 nm radius for a fixed accelerating voltage $V_A=-500$ V and fixed Einzel lens voltage $V_E=-380$ V vs the difference V_T-V_A, where V_T is the tip voltage. The overall focusing varies because the strength of the entrance lens at the first aperture varies.

radius is decreased. The distance between the atomic sized emitter and the first aperture needs to be several microns in this case.

The practical geometry for making measurements using this microscope is not as convenient as a high energy microscope because of the very short focal length. The simplest methodology is to construct the microscope at the end of a microtip, which can be positioned at the required focal distance from the sample. This geometry ensures that the backscattered electrons can be detected, while the scanning can be achieved by moving either the sample or the microscope using conventional piezodevices. This is entirely analogous to a conventional scanning tunnelling microscope (STM) with the STM nanotip being replaced by a focused electron beam. However because the depth of field is large ($\geq$50 nm), then the distance of the microtip to the sample is easier to maintain during scanning, and one can, in addition, adjust the voltage on the lens to maintain a focus. This means that the speed of scanning will be significantly faster than a STM and, at the highest resolution, should be greater than a conventional scanning electron microscope (SEM) because the beam current is approximately 10^3 times larger.

III. IMPLICATIONS

It is worthwhile noting the advantages that arise from the ability to focus low energy electrons to atomic dimensions. First the instrument is considerably simpler and does not require high voltages so that the overall packaged size will therefore resemble an STM. However the most important aspect is that the elastic scattering cross section of electrons is much larger than at the higher energies of conventional instruments and will allow one to image atoms and identify atomic species from the elastic scattering alone (the most intense channel), since the cross section for this varies as the square of the atomic number. Furthermore it is possible to generate a nanotip from cobalt wire[6] and hence generate polarized electrons for magnetic studies of surfaces. Also, since this energy is within the low energy, electron diffraction (LEED) regime, it would appear that it is now possible to directly sequence a single strand of DNA from the forward and backward diffraction pattern when the beam is focused to a few nanometers and is then scanned laterally along the strand. (It may be necessary to use two beams or rotate the strand to avoid masking by the spiral DNA backbone.) Using LEED to unravel the structure of single protein molecule is more difficult since multiple scattering will predominate. However it may be feasible to measure the surface topography of a single protein molecule if the electron energy is below 100 eV and the protein is rotated in the beam so that only the back-scattered electrons are recorded. The protein can be fixed in the electron beam by tagging a fluorescent dye to the protein and holding it using a linearly polarized, standing-wave laser beam. This ensures that the protein is held at a fixed angle determined by the dipole moment of the dye and will be particularly effective if the molecule is sufficiently laser cooled. For the DNA sequencing the electron beam is focused to a diameter of 2–3 nm (20–30 Å), and because the beam is effectively coherent, it is possible to make a hologram[8] of the base pairs in the beam. However for a rapid sequencing it will only be necessary to obtain a signature in the diffraction pattern from several detectors positioned around the focal spot as the beam is scanned along the strand. The radiation damage cross section for double-strand breaks[9] is much smaller than the elastic scattering channel particularly if the electron energy is less than 50 eV, so that a (rapid) scan rate, which does not produce double-strand breaks and yet provides sufficient "fingerprint" data, is almost certainly possible even though the wavelength at this energy prevents the generation of a complete hologram, which defines the positions of the atoms to better than several angstroms. It should be noted that the lateral positional stability of the DNA is not critical since the density of electrons at nanoamperes of current is extremely low so that the movement during the passage of a single electron is much smaller than 1 Å. Unlike the single protein a stretched DNA strand can be held in the beam using laser tweezers so that angular variations are not a problem. The beam width must therefore be significantly larger than the diameter of the DNA strand.

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