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Nanofabrication and the realization of Feynman's two-slit experiment

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Two nanosized slits are opened by focused ion beam milling in a membrane to observe, with a transmission electron microscope, electron interference fringes. Then, on the same sample, one of the slits is closed by focused ion beam induced deposition and the corresponding transmitted intensity is recorded. The comparison between the two measurements provides an impressive experimental evidence of the probability amplitude of quantum mechanics following step by step the original idea proposed by Feynman [*The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1966), Vol. 3, Chap. 1]. © *2008 American Institute of Physics*.
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The recent advances in nanoscience and nanotechnology are making possible the realization of experiments which were formerly classified as thought or ideal experiments, originally conceived in order to highlight some of the more puzzling or paradoxical aspects of a new theory. One of the most intriguing in this class is the two slit electron interference experiment, which according to Feynman[1] "contains all the mystery of quantum mechanics."

The parts of the experiment consisting in the observation of the electron interference fringes[2] and their statistical buildup[3,4] have been realized several years ago in different times and with different apparatuses.

In this letter, exploiting both the ion milling and the ion deposition nanotechnological capabilities of a focused ion beam[5] (FIB) to prepare a suitable sample, and a conventional transmission electron microscope (TEM) as a low-angle diffraction camera, we will show how it is possible to realize, following step by step the original idea proposed by Feynman,[1] the still lacking part of the two slit experiment concerning the physical meaning of the probability amplitude of quantum mechanics.[1]

The experimental setup exploited in the present work is sketched in Fig. 1. The slits were fabricated by FIB milling on a commercial silicon nitride membrane window commonly used for TEM sample preparation. The sample consisted of a 3-mm-diameter, 200-μm-thick silicon frame, with a 100×100 μm^2 square window at the center, covered with a bilayer formed by 500-nm-thick silicon nitride membrane and a further deposition of a 100-nm-thick Au film on the membrane before opening the slits. This material stacking has been selected to optimize the electron transmittance gradient between the open slits and the surrounding material, a necessary condition to be fulfilled in order to make a comparison between the intensities recorded in the far field for the two configurations of the sample, i.e., both slits open versus one slit open.

In fact, in a previous experiment, we observed that a 500-nm-thick silicon nitride membrane was not thick enough to significantly reduce the electron transmittance from the substrate.[6] FIB milling was performed with a dual beam apparatus (FEI Strata DB 235 M) that combines a 30 keV Ga^+ FIB with a thermal field emission scanning electron microscope (SEM), having resolutions of 6 and 2 nm, respectively. The system allows nanoscale machining by ion milling and ion beam assisted deposition from metallorganic gas precursor directly injected into the specimen chamber, with the simultaneous control of the work in progress by high-resolution SEM imaging. To open the slits, a 10 pA beam, corresponding to a nominal spot size of 10 nm, was scanned over two 50×750 nm^2 boxes, 450 nm spaced, 40 s for each box. The passage through the bilayer was monitored by detecting change in brightness of the ion-induced secondary electron emission. To close one of the slits a Pt strip was deposited by ion beam induced deposition of a Pt-metallorganic gas precursor (chamber pressure $P=5 \times 10^{-6}$ mbar), using a 1 pA ion beam scanned over a rectangular pattern 1 μm long, 250 nm wide.

A conventional TEM-JEOL 2010, 200 keV, relativistic corrected de Broglie wavelength, $\lambda_{electron}=2.507$ pm—operating in the low-angle Fraunhofer diffraction mode equipped with a charge coupled device (CCD) 1024

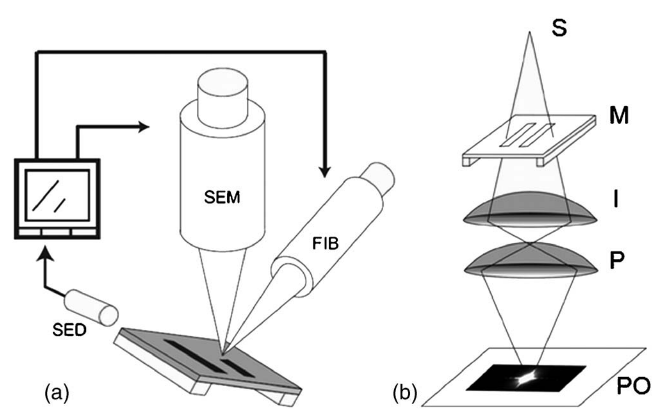

FIG. 1. Experimental setup: (a) Sketch of the FIB/SEM apparatus with the secondary electron detector. (b) TEM: S, demagnified electron source; M, Au/Si_3N_4 membrane with two open slits; I, intermediate lens; P, projector lens; and PO, observation plane, optically conjugated with the source.

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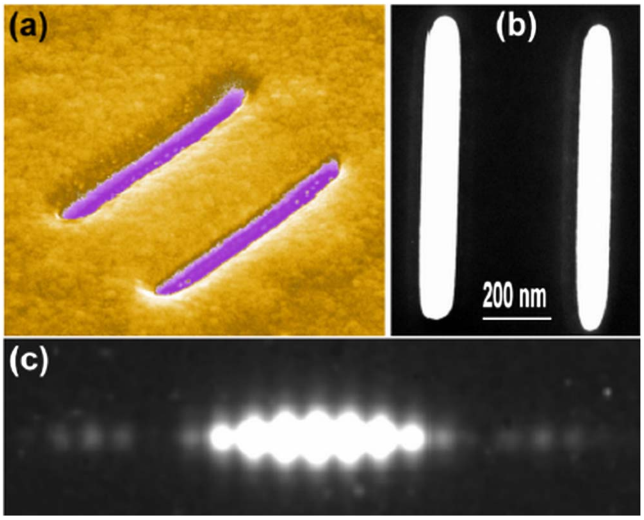

FIG. 2. (Color online) (a) SEM image of the two slits opened by FIB milling (yellow: gold, violet: silicon nitride). (b) TEM image of the transmittance of the slits, 83 nm wide, 420 nm spaced. (c) Fraunhofer electron diffraction pattern showing the two slit interference fringes superimposed to the intensity transmitted by each slit.

$\times 1024$ pixels camera model GATAN 694—has been employed to perform the role of the diffraction apparatus necessary to observe the transmitted intensity at an equivalent distance from the slits, i.e., camera length, of about 100 m. The CCD detector, though not a single electron detector, is a digital device characterized by a wide linear response to the incoming electrons (14 bits), thus allowing the quantitative recording of electron intensities. In addition, in a TEM equipped with thermoionic LaB_6 electron source, like the one of the present experiment, the very low illumination intensity adopted to satisfy the lateral coherence request for interference fringes observation, in conjunction with the relatively low source brightness, yields a negligible probability of simultaneous presence of more than one electron along the path from the source to the detector.[7] In the present experiment, in order to have enough lateral coherence at the plane of the slits ($\sim$500 nm), the condenser aperture and the spot size were selected as small as possible but, at the same time, ensuring enough signal-to-noise ratio at a reasonable exposure time of 170 s on the whole CCD area sampled with 512×512 pixels. This detector setup, characterized by a pixel size of about 50 μm^2, allows one to neglect the effect of the YAG scintillator point spread function on the fringe contrast.[8] The electron energy loss spectrometer of a GATAN GIF®200 imaging filter, located below the microscope CCD camera, has been used to determine the ratio between the "zero loss" ($\Delta E \leqslant 2$ eV) intensity transmitted by the Au/Si_3N_4 and by a single slit. A ratio lower than 10^{-3} is found, thus justifying the choice of Au deposition on top of the Si_3N_4 to minimize the transmittance from the membrane.

In Fig. 2(a) the SEM image of the slits, in false colors, is shown; the corresponding TEM image is reported in Fig. 2(b). The slits look very similar and measure a=83 nm in width (mean value) and d=420 nm in spacing. In Fig. 2(c) is reported the Fraunhofer electron diffraction pattern, clearly displaying the interference fringes modulating the single slit diffraction intensity envelope.

Nevertheless this is not, however, the whole of the Feynman experiment. In fact, he also proposed to block one of the slits in order to obtain the probability distribution of the electrons coming from a single slit and to compare it with the result obtained in the previous case.

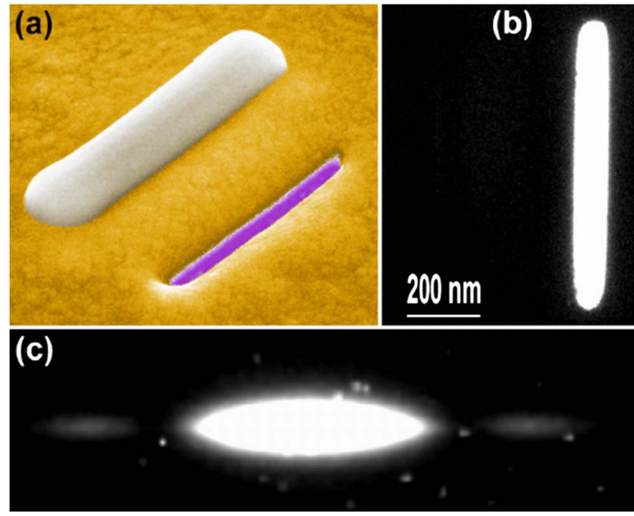

FIG. 3. (Color online) (a) SEM image of the two slits after the site-selective FIB deposition of Pt material (gray) blocking the left slit. (b) TEM image of the same area showing the still open right slit. (c) Fraunhofer electron diffraction pattern showing the typical single slit diffraction pattern.

Exploiting the FIB localized-deposition capability, we were able to close one of the slits of the sample by growing a 100-nm-thick Pt strip on top of it, leaving the second nearby slit open. In Fig. 3(a) the SEM image of the modified sample is shown.

The material deposited over the left slit is clearly visible (gray), while the nearby slit appears substantially unmodified at this spatial resolution scale. In Fig. 3(b) the corresponding TEM image of the total transmittance of the sample is shown. Indeed, a small but observable width reduction (from 83 to 76 nm) in the transparent slit is detectable in this image. As in the previous case, in order to compare the intensities transmitted by the closed slit and by the open one, we have recorded the corresponding electron energy loss spectrum (not reported here), giving a ratio of about 10^{-2} between the two zero loss peaks. The Fraunhofer electron diffraction pattern of the open blocked/slit pair is shown in Fig. 3(c). The interference modulation is not visible anymore here, and the pattern looks very similar to the envelope of the fringes shown in Fig. 2(c).

Line scans across the two diffraction patterns reported in Figs. 2(c) and 3(c) are shown in Fig. 4. To account for variations in recording/illumination conditions of the two diffraction pattern and to enable a more detailed comparison between the diffracted intensities, the intensity values have been normalized to the single slit maximum. The clear evidence that the intensity recorded with both slits open is not the sum of intensities from each slit alone gives an impressive proof of Feynman's interpretation of the experiment in terms of interference of electron waves.[1]

Nevertheless it must be observed that the fringe visibility parameter, $V=(I_{max}-I_{min})/(I_{max}+I_{min})$ measurable from the five most intense interference fringes in the central diffraction spot (V=0.43), does not reach the ideal unitary value corresponding to a minimum intensity equal to zero between two adjacent maxima. This effect, due to the finite dimension of thermoionic LaB_6 electron source used in the experiment,

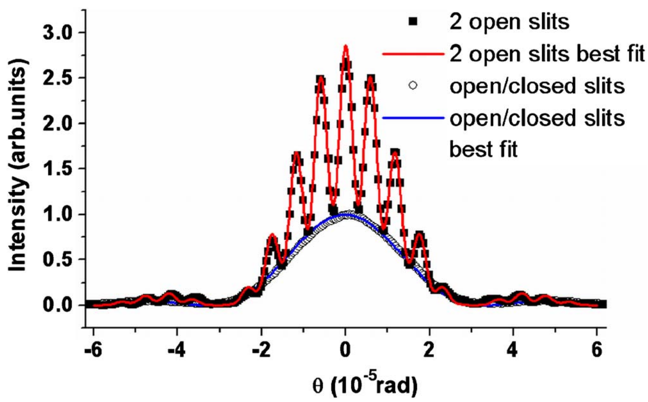

FIG. 4. (Color online) Comparison between the intensity profiles extracted from line scans three pixels wide across the maxima of Fig. 2(c) (two slits, black squares) and Fig. 3(c) (single slit, open circles). The red line is the best fit of Fig. 2(c) data, obtained with the two slit interference function in the case of partial coherence with the following parameters: $a_{\text{double slit}} = 82.8 \pm 0.3$ nm, $d = 418.8 \pm 0.7$, and $V = 0.426 \pm 0.006$. The blue line is the best fit of Fig. 3(c) data, obtained with a slit width $a_{\text{single slit}} = 76.0 \pm 0.2$ nm.

can be conveniently described by means of the mutual coherence function.[9] Therefore, in order to set up a least-squares fitting procedure aiming to extract both slit width and slit spacing from diffraction patterns, the two slit intensity profile has been simulated by using the expression describing the interference of two partially coherent beams diffracted by the two rectangular slits, width a and spacing d, given by[10]

$$I(\theta) = N[\sin(\beta)/\beta]^2[1 + V\cos(2\omega)],$$

where $\beta = (\pi a \sin\theta)/\lambda$, $\omega = (\pi d \sin\theta)/\lambda$, $N=2$, and θ is the diffraction angle. Here a, d, and V are the fitting parameters to be compared with the corresponding values measured in real space.

The red line reported in Fig. 4 represents the best fit of the experimental two slit intensity data obtained with the following parameters: $a_{\text{double slit}} = 82.8 \pm 0.3$ nm, $d = 418.8 \pm 0.7$ nm, and $V = (0.426 \pm 0.006)$. The a and d values (the first related to the envelope and the second to the interference fringe spacing) obtained by the fitting procedure show a remarkable agreement with the values measured from the images. In addition, by assuming a uniform circular source,[10] the fringe visibility is given by $V = 2J_1(2\pi\alpha_s d/\lambda)/(2\pi\alpha_s d/\lambda)$, where J_1 is the first order Bessel function of the first kind and α_s is the beam convergence. From the previously reported best fit parameters it turns out that $\alpha_s \sim 2 \times 10^{-6}$ rad. It must be noted that with a field emission electron source, whose brightness and coherence are at least two orders of magnitude higher than the thermionic one, a value of V very close to unity can be readily obtained.

The fitting of the single slit intensity profile has been carried out with the same function fixing $N=1$, $V=0$ and considering the slit width a as the only fitting parameter. The best fit (blue line) provides a slit aperture $a_{\text{single slit}} = 76.0 \pm 0.2$ nm, in very good agreement with the values obtained from the image of Fig. 3(b).

The striking correspondence between the experimental data and the calculated intensity profiles for both the two slits and the single slit case certainly provides a straightforward way to introduce the probability amplitudes of quantum mechanics.

In addition the difference between the full width of the central maxima of the two intensity profiles, $\Delta\theta_{\text{two slits}} = 6 \times 10^{-5}$ rad and $\Delta\theta_{\text{single slit}} = 6.6 \times 10^{-5}$ rad, can be ascribed to the small shrinkage of the open slit after Pt deposition on its walls.

In conclusion, we have presented an experimental realization of two slit Feynman's experiment by means of FIB nanotechnology and TEM diffraction, which represents a considerable improvement with respect to the pioneering experiments of Jönsson, whose slits were in the micrometer range and the experiment required a dedicated electron optical bench.[2] The comparison between two and single slit electron transmitted intensities shows a remarkable agreement with theoretical prediction, providing evidence for the interpretation of the experiment in terms of the complex probability amplitudes of quantum mechanics.

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[1] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1966), Vol. 3, Chap. 1.
[2] C. Jönsson, Z. Phys. **161**, 454 (1961); Am. J. Phys. **42**, 4 (1974).
[3] P. G. Merli, G. F. Missiroli, and G. Pozzi, Am. J. Phys. **44**, 306 (1976).
[4] A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Esawa, Am. J. Phys. **57**, 117 (1989).
[5] *Introduction to Focused Ion Beams: Instrumentation, Theory, Techniques, and Practice*, edited by L. A. Giannuzzi and F. A. Stevie (Springer, New York, 2005).
[6] S. Frabboni, G. C. Gazzadi, and G. Pozzi, Am. J. Phys. **75**, 1053 (2007).
[7] Considering a brightness $B \sim 10^7$ A/srcm^2, a beam divergence of about 10^{-6} rad, a current on a unit CCD surface $i \sim 10^5$ e/s, and an electron speed $v \sim 2 \times 10^8$ m/s, it results that the expected mean distance between two electrons into the TEM column is $L = v/i \sim 10^3$ m.
[8] W. J. de Ruijter and J. K. Weiss, Rev. Sci. Instrum. **63**, 4314 (1992).
[9] P. Hawkes, Adv. Opt. Electron. Microsc. **7**, 101 (1978).
[10] M. Born and E. Wolf, *Principles of Optics*, 6th ed. (Pergamon, Oxford, 1980), Chap. X.