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Elastic and inelastic electrons in the double-slit experiment: A variant of Feynman's which-way set-up

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ABSTRACT

Modern nanotechnology tools allowed us to prepare slits of 90 nm width and 450 nm spacing in a screen almost completely opaque to 200 keV electrons. Then by covering both slits with a layer of amorphous material and carrying out the experiment in a conventional transmission electron microscope equipped with an energy filter we can demonstrate that the diffraction pattern, taken by selecting the elastically scattered electrons, shows the presence of interference fringes, but with a bimodal envelope which can be accounted for by taking into account the non-constant thickness of the deposited layer. However, the intensity of the inelastically scattered electrons in the diffraction plane is very broad and at the limit of detectability. Therefore the experiment was repeated using an aluminum film and a microscope also equipped with a Schottky field emission gun. It was thus possible to observe also the image due to the inelastically scattered electron, which does not show interference phenomena both in the Fraunhofer or Fresnel regimes. If we assume that inelastic scattering through the thin layer covering the slits provides the dissipative process of interaction responsible for the localization mechanism, then these experiments can be considered a variant of the Feynman which-way thought experiment.

1. Introduction

Over the last few years, we have endeavored to carry out, by means of ion and electron beam nanofabrication and modern electron microscopes, the thought or gedanken experiment proposed by Feynman concerning the double-slit experiment with single free electrons which contains most mysteries of quantum mechanics [1,2].

The experiment consists of three parts: the first concerns the observation of interference fringes in a double slit set-up [3–6]. The build-up of the interference patterns by the single electrons has also been observed early in the Fresnel images of an electron biprism [7,8] and recently in the Fraunhofer image of a two-slit set-up [9–12].

The second part discusses the comparison of the electron distributions when one of the slits is closed [13], and its analysis leads to the idea of probability amplitude. The experiment has also been done in a controlled way by stopping one of the two beams in the Fraunhofer image of an electron biprism [14] or in the Fresnel image of two slits [11].

The third, subsequently renamed which-way (or which-path), aims at demonstrating that when the set-up is modified in order to obtain the information about which slit the electron passes through, then the interference phenomena disappear. In order to find a mechanism that is able to locate the electrons, our attention was focused on inelastic scattering as the dissipative process of interaction responsible for the localization mechanism within a region having a radius of a few tens of nanometers [15,16]. Moreover, especially plasmon inelastic scattering has been thoroughly investigated both theoretically [17,18] and experimentally [19–23] as regards its effect on the coherence properties of the electron beam, confirming that the radius of the coherence patch amounts to about 30 nm.

On the basis of the aforementioned results, in this paper we investigate what happens in a two beam interference experiment when both slits (of width 90 nm and 450 nm apart) are covered by a layer of material, where the electron can undergo inelastic scattering processes. Our expectations for this experiment were as follows: assuming a constant thickness of the layer, for the elastically scattered electrons nothing should change with respect to the case of bare slits, apart from a reduction of the overall intensity

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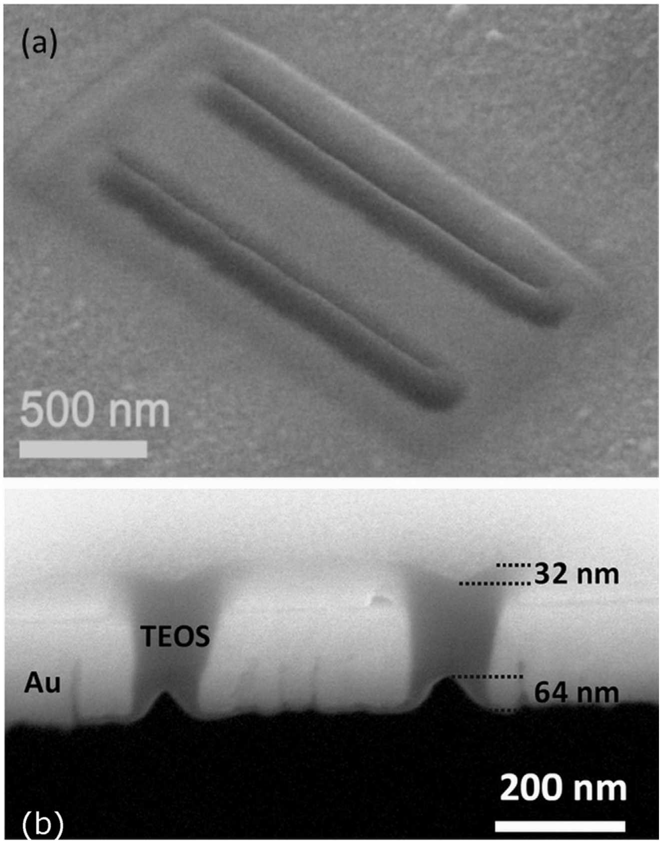

Fig. 1. (a) SEM image of two slits covered by a transparent film; (b) SEM image of a FIB cross-section.

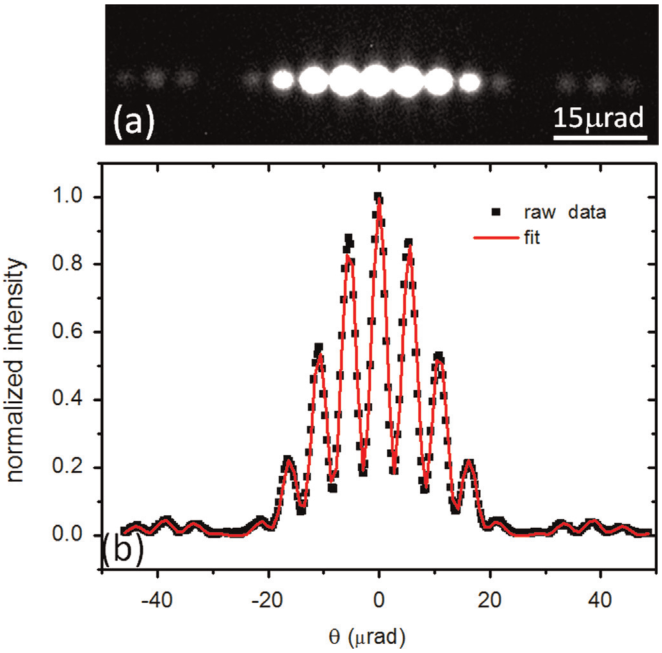

Fig. 2. Fraunhofer image of the two slits with no layer (a). The two-beam interference are better highlighted by the line-scan (b), where the continuous line is the best fit of the experimental data.

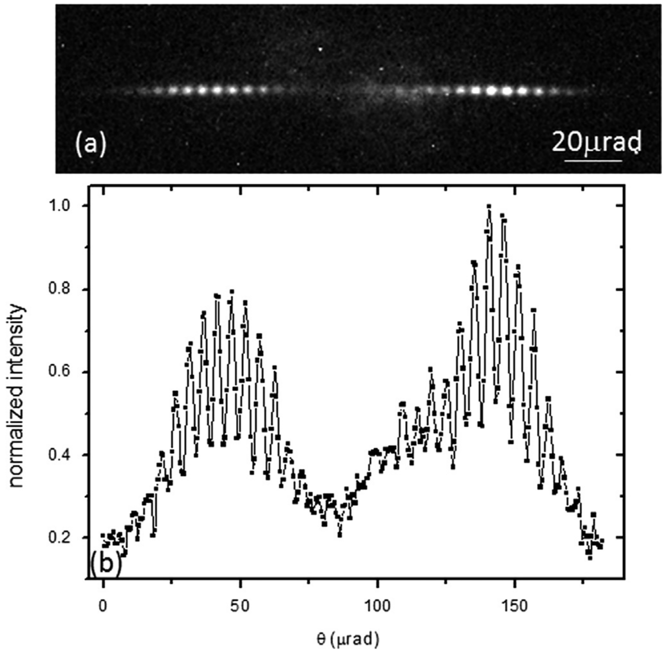

Fig. 3. TEM elastic Fraunhofer image (a) and line scans (b) of the two covered slits. The diffraction image and the corresponding line scan, averaged over five pixel, clearly show again interference phenomena, although quite different from the expectations.

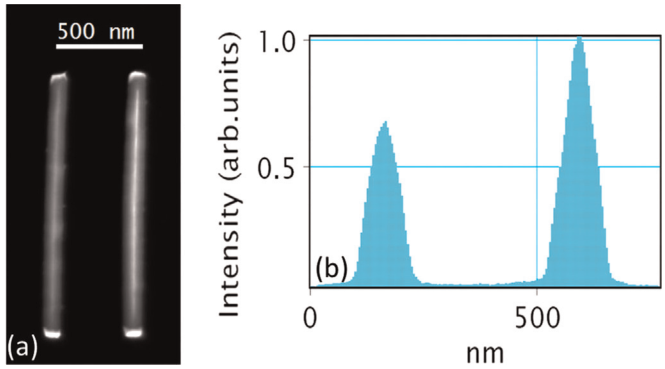

Fig. 4. TEM image (a) and line scans of the elastic electrons across the two covered slits, averaged over the whole slit length (b).

and the presence of a constant phase shift due to the mean inner potential of the film, which cancels in the Fraunhofer image. In the case of inelastic electrons, although some interference effect could still be expected in the diffraction image (the slit width of 90 nm is not too large with respect to a coherence patch of 30 nm), they should be completely canceled out in the two beam interference image by the localization process, as the slit separation is more than an order of magnitude larger than the coherence patch (450 nm vs 30). It follows that, according to Feynman analysis [1], no fringes should be present in the image taken with the inelastic electrons. These considerations were confirmed by a preliminary experiment where layers of material of different thickness were deposited only on one of the slits [24].

The experiment we report here is divided in two parts. The first one has been carried out covering the slits with a carbonaceous layer by means of Electron Beam Induced Deposition (EBID). However, the intensity distribution of the plasmon loss-inelastically scattered electrons was so broad that the signal recorded with a transmission electron microscope (TEM) equipped with a LaB_6 gun was buried in the noise. On the contrary, the elastic images were richer in detail with respect to our expectations and their interpretation was very useful for the second part of the experiment. In this part, we used a TEM equipped with a Schottky field emission gun (SFEG) and we deposited over the slits an aluminum layer, whose Electron Energy Loss Spectrum (EELS) is characterized by a more intense plasmon peak. We were thus able