Quantitative Evaluation of Spatial Coherence of the Electron Beam from Low Temperature Field Emitters

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By using multiwalled carbon nanotubes as an element of a nanobiprism, we evaluated quantitatively the coherence of electrons emitted from tungsten tips at room temperature and 78 K, and found an enhancement of coherence at 78 K. The increase of the transverse coherence length of the electron beam agreed well with that of the inelastic mean free path of electrons in solids, demonstrating the direct relationship between the coherences of the electron beam and the original electronic states. On the basis of this experimental fact, we comment on the interpretation of recent Hanbury Brown–Twiss type experiments for electrons reported by Kiesel *et al.* [Nature (London) **418**, 392 (2002)].

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Coherence is one of the most fundamental concepts of wave physics including physical optics and quantum mechanics. It is at the heart of the discussion of interference, diffraction, holography, and phase contrast imaging [1], and of the interpretation of quantum mechanical phenomena, such as Hanbury Brown–Twiss effect [2], Aharonov-Bohm effect [3], entanglement, etc. In classical terms, the expression ‘‘highly coherent waves’’ means that the waves vibrate in unison for a long period of time over a wide space. The degree of coherence of waves is determined by their source. A source is called incoherent when the waves it emits do not vibrate in unison at separate positions on the source. At a distance, however, the waves vibrate in unison over a finite space whose dimension is called the transverse coherence length ξ_T. ξ_T is inversely proportional to the source size and the distance from the source. Naturally, efforts for enhancing the spatial coherence of waves have been focused on reducing the source size for incoherent sources.

Field emission (FE) electron sources have been widely used for producing a highly coherent electron beam because of its inherently small source size. But FE sources have usually been considered as incoherent sources [2], despite the finite spatial extent of electron wave functions inside FE sources. If a FE source is partially coherent, i.e., the waves vibrate in unison over the finite area on the source, the coherence of the waves at a distance can also be improved by enhancing the coherence of the source. In this Letter we report the first experimental demonstration that FE sources are partially coherent even at room temperature (RT). Cooling a FE tip led to further enhancement of the coherence of the emitted e-beam, showing the direct relationship between the coherence of emitted e-beams and the original electronic states.

In electron interference experiments, a biprism is one of the most powerful instruments for characterizing or for exploiting the coherence of an electron beam because of its simple structure and the high signal intensity used for analysis [4]. The conventional biprism consists of a thin biased filament, placed between two earthed plates. The incoming electron wave is divided into two partial waves by the filament. These waves are deflected by electric fields around the filament to meet again on the observation screen, generating an interference fringe pattern. The experimental data on the visibility of the fringes as a function of the width of the interference band provide a quantitative evaluation of ξ_T on the screen: raising the electric potential of the filament leads not only to a widening of the band of the interference pattern but also to a degradation of the visibility of interference fringes [4]. As the width of the interference band becomes larger than the ξ_T value of coherent electron waves, the interference fringes disappear completely. Hence, a critical bandwidth W_c for the disappearance of the fringes corresponds to the ξ_T value of the electron wave at the observation screen. Once ξ_T is measured, the effective source size r_{eff} is obtained by using the van Cittert-Zernike theorem [5],

$$r_{\mathrm{eff}} = \frac{\lambda \cdot l_s}{\pi \cdot \xi_T}, \quad (1)$$

where l_s is the distance between the screen and the electron source, and λ the wavelength of the electron. If the electron source is incoherent (partially coherent), the effective source size is equal to (smaller than) its real geometrical size.

Recently, a carbon fiber fixed on a submicron scale hole in a copper grid was shown to play the role of a nanobiprism in a projection microscope, because the potential around the fiber bends with the bias voltage between the tip and the fiber [6]. This system provides some advantages over a conventional biprism: the fiber diameter is extremely small (a few nm), which allows for the operation of the nanoscale biprism with a small distance between the source and the biprism, and for the combination with projection microscopy. As a result, high-quality interference fringes are produced without magnifying lens systems, as shown in Fig. 1.

In the present experiment, multiwalled carbon nanotubes (MWCNT) deposited on a holey carbon grid with typical hole radii of a few hundred nanometers are used as a nanobiprism. The MWCNT plays the role of the biased filament in a normal nanobiprism; namely, it divides the electron wave into two parts, and, at the same time, it deflects them so that they overlap. As shown schematically in Fig. 1(a), one isolated nanotube on a holey grid is placed just in front of the emitter, and can be positioned precisely with the 3D-adjusting system in the same way as

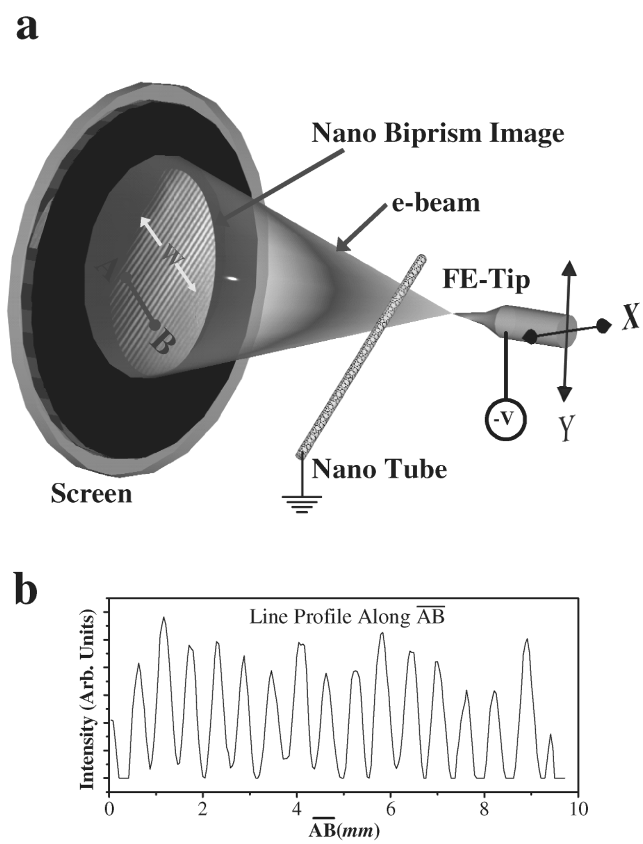

FIG. 1. Experimental arrangement (a) and the line profile of beam intensity along AB on the screen (b). The FE emitter is driven by a piezotube. When an electron wave from the FE emitter irradiates a multiwalled carbon nanotube (MWCNT), it is deflected by the electric field distortion around the MWCNT and forms a biprism interference pattern on the screen. Because the emitter-MWCNT distance (0.1–10 mm) is much smaller than the MWCNT-screen distance (16.5 cm) and the wavelength of the electron is quite large (>1 Å) due to its low kinetic energy (<100 eV), the interference fringe spacing is quite large (>0.4 mm) on the screen, enabling the observation of a fringe pattern with bare eyes.

in the scanning tunneling microscopy (STM) technique. An isolated tube is irradiated by electron waves propagating radially from a field emitter. Its image, magnified by a factor of 10×10^6, is projected on a screen at a distance $l_s = 16.5$ cm from the tube as shown in Fig. 1(a). By using the magnified image of such a projection microscope, one of the best nanobiprism systems was selected for the measurement of ξ_T. The base pressure in the chamber was less than 1×10^{-8} Pa [7]. In this work, we measured ξ_T of electron waves emitted from polycrystal tungsten tips with radii of several hundreds of nm, at two tip temperatures: RT and 78 K.

Sharp interference fringes are always observed by the nanobiprism as shown in Fig. 1(a). Figure 1(b) shows a line profile of electron intensity along AB in Fig. 1(a). No background was subtracted. The line profile yields an average fringe spacing of 0.58 mm with a standard deviation of 0.024 mm. The regular spacing is a clear experimental evidence of the normal action of the biprism. In addition, we found that the width W of the interference band increased, and the fringe gradually blurred to become completely invisible, as the source approaches the biprism. The phenomena were the same as those observed using a conventional biprism controlled by a bias voltage. We measured the curve of visibility V as a function of the bandwidth of interference fringes W by changing the tip-biprism separation. The visibility V is defined as

$$V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}). \tag{2}$$

Here, $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities of the fringes, respectively [1]. From the visibility curve, the values of ξ_T on the screen were obtained. Prior to the low temperature experiment, ξ_T was measured at RT for six tungsten tips. Depending on the different emission sites on the same tip, and also on the tips, the ξ_T values varied in the range of 10–20 mm, which yields effective source sizes of 0.4–0.7 nm. Considering the typical tip radius of 50 nm of the conventional tips, one can notice that the estimated sizes have implausibly small values compared with the physical tip radius, which indicated that the tips are partially coherent sources.

In solids, in general, the inelastic mean free path of conduction electrons ξ_{in} increases with decreasing temperature because of the reduction of phonon scattering. Hence, interference of electrons traveling along different paths occurs if the path difference is shorter than ξ_{in} in solids. The electric resistivity of tungsten decreases from 5.5×10^{-8} to 0.6×10^{-8} Ω cm in inverse proportion to the temperature in the range from RT to 80 K [8]; ξ_{in} changes from 16 to 140 nm with such a cooling. If the tungsten tip is cooled from RT to low temperature, thus, one can expect a large enhancement of the coherence of the emitted electrons due to the increase of ξ_{in}. This turned out to be the case, as shown below.

Figures 2(a) and 2(b) show the interference fringes of electron beams emitted from the same tip at RT and 78 K, respectively. The visibility curves V are plotted against the observed width of the interference band, W in Fig. 3. The data points represented by triangles, $B1$, and circles, $B2$, at RT in Fig. 3 were obtained by using different nanobiprisms. Both results yielded similar ξ_T values of $\sim$13 mm as shown in Fig. 3, which proves that the ξ_T measurement does not depend much on the nanobiprism employed.

As one can see clearly in the patterns of Figs. 2(a) and 2(b), the fringes at 78 K are much sharper than those at RT, indicating their high visibility. The fringes blurred with the widening of the interference band, but they did not disappear even for values of W above $\sim$70 mm, the maximum diameter of the screen. The ξ_T value at 78 K was longer than $\sim$70 mm, which is more than 5 times as long as ξ_T at RT (13 mm).

The ratio K $(=\xi_T/l_R)$ of coherent length to beam radius is constant for all the positions of electron optics in electron microscopy, which was proved theoretically and experimentally by Pozzi [9]. Under the same assumption in projection microscopy, the coherence length ξ_T at the tip was estimated to be 5–10 nm at RT and $\sim$35 nm at 78 K. These estimated lengths at the tip are consistent with our previous results of Young's fringes observed in the FE patterns from MWCNT [10]; electron waves from different sites separated by a few nm can interfere with each other on a screen, demonstrating that the coherence length of the electronic state on the MWCNT surface is longer than a few nm at RT. The estimated ξ_T values are several times or several tens of times as long as the Fermi wavelengths λ_F of the solids. Similar data were also found in STM images. STM observations on electron standing waves have shown that the coherence length of the electrons at the Fermi level is finite even at RT [11], and increases with decreasing temperature [12].

FE is a tunneling process of electrons from electronic states inside solids into vacuum. In quantum mechanical terms, the partial coherence of a FE source means that wave functions of electrons have finite spatial extent and can overlap during the tunneling. The overlap of wave functions induces anticorrelation of field-emitted electrons on average, because two indistinguishable fermions must exclude each other by the Pauli principle.

In a recent coincidence experiment [2], Kiesel *et al.* attributed the attenuation of coincidence rates of electrons to electron anticorrelation which, they proposed, was built up during propagation because the FE source was incoherent. As indicated in this Letter, however, FE sources are partially coherent even at room temperature with a coherence length of a few nanometers. To

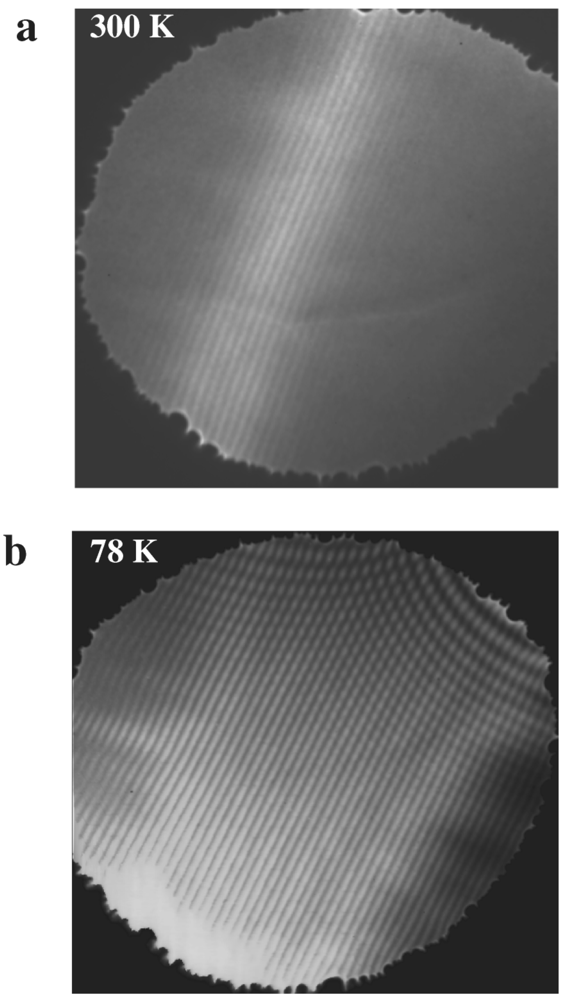

FIG. 2. Biprism interference patterns just before the complete blurring of fringes at room temperature (RT) (a), and 78 K (b). The interference fringes at 78 K extend beyond the circular boundary of PM images ($\phi = 25$ mm). Measurements at RT were performed by using two different nanobiprisms ($B1$ and $B2$), producing nearly similar ξ_T values.

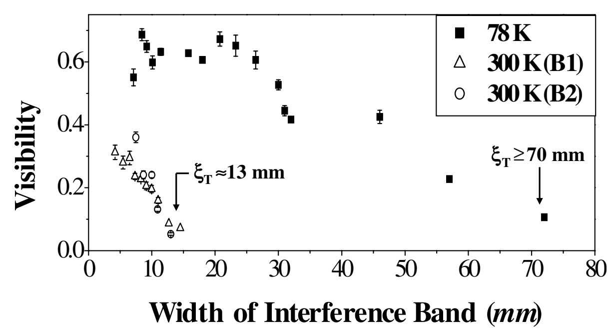

FIG. 3. The evolution curves of visibility at RT and at 78 K as a function of the width (W) of the interference band. The data points of $B1$ and $B2$ at RT were obtained by using different nanobiprisms. The visibility, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} (I_{min}) is the maximum (minimum) intensity of the interference pattern, is a measure of the sharpness of interference patterns. The visibility curves yield $\xi_T \sim 13$ mm and ≥ 70 mm at RT and 78 K, respectively, as indicated by arrows.

illuminate the two electron detectors coherently, Kiesel *et al.* raised the angular magnification of the electron wave. As is well known in field emission microscopy [13], electrons emit nearly perpendicular to the surface of a field emitter and an electron detector with a limiting aperture can see only a limited part of the FE area, a few nm. So two detectors in the coincidence experiment normally see different parts of the emission area, which we denote effective areas A and B. Tracing the change of the e-beam trajectory directly shows that raising angular magnification decreases the distance between the effective areas A and B, or effectively decreases the distance between the two detectors. If the distance between the effective areas A and B is comparable to the coherence length of electrons inside solids, electrons tunneling through the effective areas A and B can be anticorrelated as recently observed in tunneling through quantum-point contacts [14]. In this regard, we point out that the reduced coincident rates observed by Kiesel *et al.* could originate from anticorrelation during coherent tunneling.

In summary, the coherence of electrons emitted from tungsten tips at two different temperatures has been evaluated quantitatively. The enhancement of the coherence at 78 K agreed quantitatively with the increase in the inelastic mean free path, $\xi_{\rm in}$ in solids calculated on the basis of the conductivity. We are now preparing 5 K experiments, under which conditions the inelastic mean free path, $\xi_{\rm in}$, is expected to increase by an additional factor of $\sim$15. These highly coherent electrons will allow developing new technology in many aspects of electron microscopy and electron holography [3], resulting in the creation of new research fields of fundamental physics concerning highly coherent electron beams such as the Aharonov-Bohm effect [3], anticorrelation of electron waves in vacuum [2] and material science and technology.

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