Microwave Guiding of Electrons on a Chip

J. Hoffrogge,[1] R. Fröhlich,[1] M. A. Kasevich,[2] and P. Hommelhoff[1,*]
[1]Max Planck Research Group "Ultrafast Quantum Optics," Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching bei München, Germany
[2]Department of Physics, Stanford University, Stanford, California 94305, USA
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We demonstrate the transverse confinement and guiding of a low energy electron beam of several electron volts in a miniaturized linear quadrupole guide. The guiding potential is generated by applying a microwave voltage to electrodes fabricated on a planar substrate, which allows the potential landscape to be precisely shaped on a microscopic scale. We realize transverse trapping frequencies of 100 MHz and guide electrons along a circular section of 37 mm length. A detailed characterization of the guiding properties in terms of potential depth and dynamic stability is given. This new technique of electron guiding promises various applications in guided matter-wave experiments such as electron interferometry.

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Electrons traveling in free space have allowed exploring fundamental physics like the wave nature of matter [1,2], the Aharonov-Bohm [3,4] and the Hanbury Brown–Twiss effect [5]. Moreover, precise control over the external degrees of freedom of electrons has proven pivotal for wholly new types of experiments such as high precision measurements of the electron's mass [6] and magnetic moment [7,8] in Penning traps. Interestingly, the confinement of electrons in the purely electric field of an alternating quadrupole [9] has rarely been considered. Recent advances in the development of planar chip-based ion traps [10–12] suggest that this technology can be applied to enable entirely new experiments with electron beams guided in versatile electromagnetic potentials. These can typically be shaped on length scales on the order of the distance between the trap center and the field-generating electrodes. Hence, miniaturized traps with microstructured electrodes allow for small and complex geometries, which have enabled quantum manipulation experiments both with neutral atoms in magnetic chip traps [13] and with ions in Paul traps [14–16]. In analogy, microstructured Penning traps, combining a static magnetic field with the electric field generated by a planar electrode geometry, have been demonstrated for the three-dimensional confinement of electrons [17]. Electron guiding in a purely electric, alternating quadrupole field has so far been realized only with macroscopic structures [18], which impedes microscopic shaping of the potential.

In this Letter, we demonstrate the transverse confinement of a low energy electron beam in a linear quadrupole guide based on microstructured planar electrodes and driven at microwave frequencies (Fig. 1). We show that a planar electrode configuration is, besides its potential to generate complex waveguiding elements, an ideal choice to realize an electron guide as it is compatible with on-chip microwave transmission line technology to feed the structure. A new guided matter-wave system might result, with applications ranging from electron interferometry to novel noninvasive electron microscopy. Furthermore, together with advanced electron sources it appears feasible to prepare and guide electrons in the transverse motional ground state in close analogy to light guided in single-mode optical fibers. Appropriately structuring the guide will allow for the (coherent) splitting and recombination of an electron beam as needed in matter-wave interferometry experiments.

The confinement of charged particles in a linear radio frequency guide relies on the time-averaged action of an oscillating electric field $E(\mathbf{r}, t) = E(\mathbf{r})\cos(\Omega t)$. In the ideal case, $E(\mathbf{r})$ is a pure quadrupole field generated by applying an alternating voltage with amplitude V to electrodes at a distance R from the guide's center [9,19]. Particles can be confined if their transverse motion is slow compared to the drive frequency Ω, which is quantified by a dimensionless

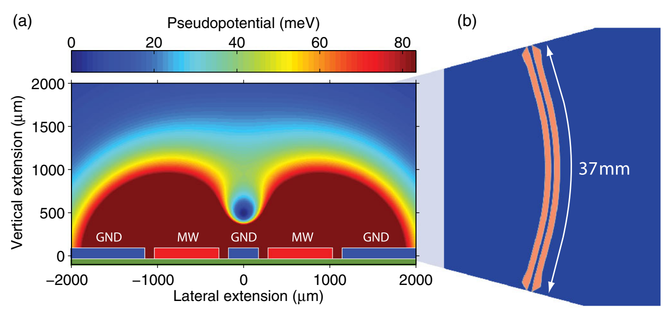

FIG. 1 (color online). Pseudopotential and guide layout. (a) Cut through the electrode plane and the pseudopotential experienced by an electron. The plotted height of the electrodes is exaggerated for illustration purposes. Guiding is achieved in the potential minimum (blue) at a distance of $R = 500\ \mu$m above the central electrode. (b) Electrode layout of the guiding structure. Electrons are guided along a bent five-wire structure and deflected by 30°. The microwave signal is applied to the red electrodes, whereas the blue regions are grounded.

stability parameter $q = (2Q/m)V/(\Omega^2 R^2)$ with Q/m the charge-to-mass ratio of the particles. Stable transverse confinement is provided for $0 < q < 0.91$. For small q, the particle's transverse motion can be approximated by that in a harmonic pseudopotential with frequency $\omega = (q/\sqrt{8})\Omega$ and depth $U = (q/8)V$.

Compared to the confinement of ions, electrons with their $\sim 10^4$ times higher Q/m require notedly different driving parameters to keep q small and at the same time generate a sufficiently large potential depth and transverse frequency. We aim at $q = 0.4$ and a potential depth of several ten milli-electron volts, demanding a drive voltage of $V \approx 30$ V. For a convenient $R = 500$ μm, still realizable with standard printed circuit board technology, a driving frequency of $\Omega \approx 2\pi \times 1$ GHz is necessary. The driving wavelength λ is still much larger than the longitudinal structure size L ($\lambda = 21$ cm vs $L = 37$ mm), which allows us to work in a standing-wave configuration.

The guiding field $E(\mathbf{r}, t)$ is generated by applying the drive voltage to a set of five electrodes on a planar substrate, in close analogy to surface-electrode ion traps [10,11,20]. In Fig. 1(a), a cut through the electrode layout is shown together with the microwave pseudopotential experienced by an electron above the substrate. Electrode widths are 350 μm for the grounded central one and 750 μm for the microwave electrodes with 110 μm gaps in between. The potential is calculated for a driving frequency of $\Omega = 2\pi \times 970$ MHz and the maximum peak voltage of $V = 33$ V available in the experiment. Guiding is achieved in the potential minimum (blue) at a distance of $R = 500$ μm above the central electrode. Near the guide center, the potential is approximately harmonic with a transverse trapping frequency of $\omega = 2\pi \times 133$ MHz. Its depth is limited to $U = 41$ meV by a saddle point forming above the center. For the on-chip microwave power available (10 W), these are the highest values of transverse trap frequency and potential depth that are experimentally achievable.

The complete electrode layout of the guide is shown in Fig. 1(b), whereas Fig. 2(a) displays a photograph of the experimental setup. The guide consists of a 37 mm curved section with a bending radius of 40 mm spanning an angle of 30°. It is fabricated by a standard printed circuit board process on a Rogers RO4350B microwave substrate with electrodes made from gold-plated copper with 40 μm thickness. Electrons are injected at one end of the structure, travel along the curve, and are ejected at the other end, where they are detected by an imaging microchannel plate (MCP). The electron gun consists of a thermal source and beam forming elements [21] with an exit aperture of 20 μm diameter. Typical beam currents for electron energies between 1 and 10 eV are on the order of several ten nanoamperes. The guide is shielded from electric fields by a metallic cover with its top plate 10 mm above the substrate [removed in Fig. 2(a)] and a grounded mesh between the substrate and MCP. Electrons with a kinetic energy of $E_{\mathrm{kin}} = 2$ eV, as typically used here, experience around four oscillations in the pseudopotential, corresponding to 44 oscillations of the driving field, while traveling along the guide. Near the edges of the substrate we have optimized the wire shape numerically in order to achieve smooth coupling into the guide [22].

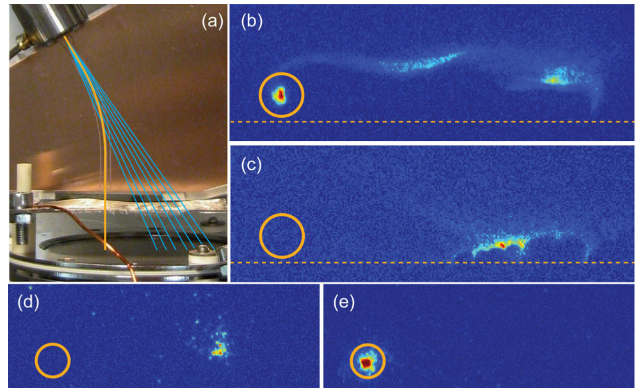

FIG. 2 (color online). Images of setup and guided electrons. (a) Experimental setup with the substrate in the center. The last element of the electron gun is visible at the top left, the imaging MCP electron detector at the bottom. Guided electrons follow the orange curve from source to MCP, whereas trajectories of unguided electrons are indicated in blue. (b) MCP image with microwave power applied. The orange circle indicates the position of the guide's exit port, the horizontal dashed line the electrode plane. The guide is operated at $\omega = 2\pi \times 100$ MHz, $U = 27$ meV, and $q = 0.3$. (c) For comparison, an image with no microwave power applied to the guide. Note that the image intensity has been increased by a factor of 2 as compared to (b). The kinetic energy of the electrons in both (b) and (c) is 4 eV. (d), (e) Images taken at 1 eV by using an improved version of the electron source: In (d) no microwave power is applied, whereas (e) shows guiding [$\omega = 2\pi \times 47$ MHz, $U = 5$ meV, and $q = 0.09$; about the same field of view as in (b) and (c)]. Here, no loss of electrons is visible.

The microwave signal is fed to the substrate via an edge-mount coaxial connector (subminiature type A). On the substrate, the signal is conducted by a coplanar transmission line on the bottom side of the substrate, which runs perpendicularly to the guide on the top side and is connected by plated-through holes of 150 μm diameter to the center of the guide. Because the electrodes' ends are open, a standing wave forms with antinodes at the beginning and the end of the guide. Because of the small length of the whole structure, the voltage difference along the guide is measured to be less than 10%. The microwave signal is directly fed from an amplifier with a maximum output power of 30 W to the substrate without using any resonating structures. With a bias tee between the amplifier and the vacuum feedthrough, static charging of the signal conductors is prevented while an additional directional coupler allows us to monitor the microwave power fed to the substrate. The power applied to the electrodes is inferred from this signal by correcting for the independently measured frequency-dependent loss of the microwave cables and the transmission line structure on the substrate.

Trajectories of guided and unguided electrons are indicated in Fig. 2(a) by orange and blue lines, respectively. Guiding is demonstrated by forcing the confined electrons on a curved path that ends on the left side of the detector when watched from behind. For appropriate settings of Ω and V we obtain a bright spot of electrons visible exactly at the position of the guide exit; see Fig. 2(b). For comparison, Fig. 2(c) shows a detector image without microwave power applied. In that case only a diffuse spot of electrons fanning out from the gun is visible to the right of the guide's exit port. The dark regions between electrons and the substrate indicate that electrons are deflected away from the gaps between the electrodes due to substrate charging. Its effect can partially be compensated by applying a voltage of up to several volts to the top plate of the metallic cover, leading to robust electron guiding for kinetic energies from approximately 1 to 5 eV.

In this proof-of-concept experiment we use a thermal electron gun that emits a rather poorly collimated beam; hence, some of the injected electrons have large transverse momenta. Furthermore, the charging of the substrate between the electrodes shifts guided electrons away from the potential minimum. Both these effects lead to loss of electrons during guiding. Those lost in the bent section are visible as faint curved horizontal line in the image center of Fig. 2(b), whereas the ones lost at the beginning of the guide form a brighter spot on the right-hand side. While these pictures are instructive to study the basic loss mechanisms of the guide, Figs. 2(d) and 2(e) show data taken with an improved version of the electron gun. It allows for much better collimation at lower beam energies (1 eV for the data shown) which also reduces substrate charging. For these data, no loss of guided electrons is visible. Future electroplated substrates with a high aspect ratio of electrode thickness over gap width should further increase the guided fraction by shielding guided electrons from exposed substrate areas [10,23].

We have characterized the guiding potential by recording the number of guided electrons as a function of potential depth U and stability parameter q (Fig. 3; raw data in terms of V and Ω are presented in Ref. [22]). It is apparent that a minimum potential depth U_{min} is necessary to counter the centrifugal force on the particles in the curved guide. As expected, when E_{kin} is increased, U_{min} also increases due to the larger centrifugal force (from $U_{\mathrm{min}} \approx$ 10 meV at 1 eV to $U_{\mathrm{min}} \approx 19$ meV at 5 eV). Furthermore, for $U > U_{\mathrm{min}}$ we observe a constant signal of guided electrons up to $q \approx 0.42$. The loss of guiding for higher q can be attributed to radio frequency heating as the micromotion of the electrons in the guide is increased.

Figure 3(d) shows the result of a numerical particle-tracking simulation of electron trajectories in the alternating field [22]. In qualitative agreement with the experimental data, we observe a loss of guiding below $U_{\mathrm{min}} \approx 22$ meV and above $q \approx 0.8$ for $E_{\mathrm{kin}} = 3.5$ eV. We attribute the differences from the experimentally recorded values to calibration errors of the microwave power fed to the electrodes, a larger transverse electron momentum in the experiment, and numerical uncertainties in the simulation. The particle-tracking results also confirm that guiding should work down to q approaching 0, where we have not been able to record data due to limited microwave power available.

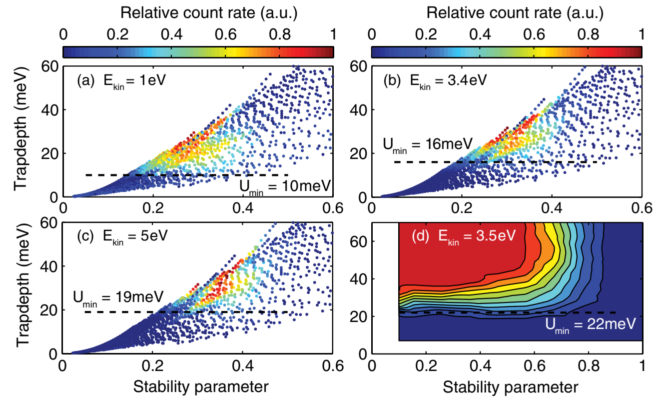

FIG. 3 (color online). Fraction of guided electrons as a function of stability parameter and potential depth. (a)–(c) Experimental data for different electron energies as indicated. With increasing kinetic energy the minimum potential depth U_{min} needed for guiding increases. Also, the guide becomes unstable for stability parameters higher than approximately 0.42. As the gain of the MCP and the beam current emanating from the electron gun vary from (a) to (c), each plot has been normalized separately. The white areas in the upper left half of the plots were not accessible for technical reasons (limited microwave power). (d) Results of a particle-tracking simulation at 3.5 eV kinetic energy. Note the different plot range of the horizontal axis. See the text and Ref. [22] for details.

The next important experimental step lies in the realization of a coherent beam splitter for propagating guided electrons similar to the Y junctions that have been envisioned for ions shuttled in surface-electrode ion traps [24]. Furthermore, scaling to a guide-to-surface distance of $R = 50\ \mu$m and a driving frequency of $\Omega = 2\pi \times$ 10 GHz would result in a system providing even faster dynamics at a transverse frequency of $\sim$1.2 GHz. Lithographic substrate patterning will allow us to extend the guiding structures to more complex geometries and to many electrons guided in separate potentials.

The possibility to realize a wholly new quantum device arises from the combination of an electron guide as demonstrated here with a single-atom tip electron emitter [2,25]. These sources have been shown to emit electrons fully coherently [26] and are Heisenberg-uncertainty limited in terms of emitter source size and transverse electron momentum. The same minimum uncertainty criterion also applies to the position and momentum of the ground state wave function in a static harmonic potential, which describes the time-averaged transverse motion of electrons near the center of the guide to a very good approximation [27]. Thus, with electron optics preserving phase space density, it should be possible to directly prepare all electrons originating from a single-atom tip in the transverse ground state of the guiding potential *without* the need for cooling. Since the ground state energy in a 100 MHz potential amounts to $E_0 = \hbar\omega/2 = 0.2\ \mu\text{eV}$, which has to be compared to the overall potential depth of $U = 41$ meV, loss of guided electrons, as observed with thermal electrons in the present experiment, will be negligible for low lying oscillator states. This represents an ideal starting point for guided matter-wave interferometry [2,28] and quantum manipulation experiments.

Technically, the high transverse frequencies will well isolate the electrons from electric field noise. The heating rate $\dot{n}$ in quanta per second is given by $\dot{n} = e^2/(4m\hbar\omega)S_E(\omega)$ with the electric noise density $S_E(\omega) \propto (1/\omega)(1/R^4)$ [29]. Scaling the results measured for ions in microscopic traps at room temperature [11] to electrons in the guide demonstrated here yields a heating rate of $\dot{n} \approx 7/\text{s}$. Thus a ground state electron can perform around 15×10^6 oscillations in the pseudopotential before being heated to the first excited state.

An electron guide together with femtosecond laser-triggered sources [30] will enable full 4D control of electrons. Hence one can envision controlled-interaction experiments between, for example, two electrons propagating in neighboring guides and interacting via the Coulomb force, closely related to what has very recently been demonstrated with ions [14,15]. Because of the smaller mass of electrons, comparable coupling strengths of $\Omega_c \approx 2\pi \times 1$ kHz can be achieved over a 10 times larger distance of 500 μm (assuming transverse coupling in adjacent guides with $\omega = 2\pi \times 100$ MHz). With $\omega = 2\pi \times 1$ GHz and $R = 50\ \mu$m the coupling strength increases to $\Omega_c \approx 2\pi \times 100$ kHz. This interaction could lead to the entanglement of confined electrons, similar to what has been proposed for electrons in Penning traps [31]. One can also envision interfacing guided electrons with other quantum systems like trapped ions, atoms, or electrons in solids. With an additional potential the guide can be longitudinally closed and converted to a 3D trap. Furthermore, it has recently been proposed to use laterally confined electrons in a microstructured potential for novel noninvasive electron microscopy [32].

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*peter.hommelhoff@mpq.mpg.de

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