Available online at www.sciencedirect.com
ScienceDirect
Physica B 403 (2008) 2015–2020
PHYSICA B
www.elsevier.com/locate/physb

Persistent current in finite-width ring with surface disorder

H.B. Chen[a], J.W. Ding[a,b,*]

[a]Department of Physics, Xiangtan University, Xiangtan 411105, Hunan, China
[b]National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China

Received 26 March 2007; received in revised form 2 November 2007; accepted 17 November 2007

Abstract

We explore the surface disorder effect on the persistent current in a finite-width ring. In the strong disorder regime, the persistent current increases with surface disorder strength, while it decreases in the weak disorder regime. The result is at variance with the observation in bulk-disordered ring. Also, it is shown that the disorder-induced changes in the persistent current strongly depend on both the ring width and radius, which show up a singular quantum size effect.

PACS: 73.23.Ra; 72.15.Rn; 73.20.−r

Keywords: Persistent current; Tight-binding; Finite-width ring; Surface disorder

1. Introduction

In a pioneering work, Büttiker et al. [1] predicted that even in the presence of disorder, an isolated one-dimensional (1D) metallic ring threaded by the magnetic flux Φ can carry an equilibrium persistent current with periodicity $\Phi_0 = h/e$, the flux quantum. The existence of persistent currents had been confirmed by the experimental observations in single/ensemble of isolated mesoscopic ring [2–7]. Except for the case of the nearly ballistic GaAs–AlGaAs ring [4], all the measured currents are in general one or two orders of magnitude larger than those predicted from the theory [8–13]. The diamagnetic response of the ensemble-averaged persistent current in the vicinity of the zero magnetic fields also contrasts with most predictions [10,11]. This means that the experimental results are not well understood theoretically so far. The persistent currents in mesoscopic rings are the subject of intensive research [14–17].

Metals are intrinsically disordered which tends to decrease the persistent currents in mesoscopic rings. To explore the disorder effect, many of the theoretical studies took the limit from 2D to 1D ring, for which different 1D ring Hamiltonians were used. For example, Kim et al. [18] investigated the behavior of persistent currents of 1D normal-metal rings with the impurity potential. The diamagnetic response near the zero magnetic fields was attributed to multiple backward scattering off the impurities. Also, Maiti et al. [19] built a simple 1D tight-binding Hamiltonian with diagonal disorder and long-range hopping integrals to account for the observed behavior of persistent currents in single-isolated-diffusive normal metal rings of mesoscopic size. In the experiments, however, the mean width of the sample ring was usually comparable to its mean radius. In such finite-width rings, it was found that the typical current I_{typ} increases with the channel number M by $I_{\text{typ}} \sim \sqrt{M}$, while the disorder-averaged current is independent of M in the ballistic regime [9], only including even Fourier components. On the other hand, confinement and surface roughness effects on the magnitude of the persistent current were analyzed in the case of the ballistic 2D metallic rings [20], which may contribute coherently to the persistent current. It was shown that the typical current increases linearly with the channel number M. These means that 1D description is oversimplified to describe quantitatively the finite-width rings in experiments.

*Corresponding author at: Department of Physics, Xiangtan University, Xiangtan 411105, Hunan, China.
E-mail address: jwding@xtu.edu.cn (J.W. Ding).

0921-4526/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physb.2007.11.010

In the presence of disorder, some works had been done on the finite-width 2D ring, focusing on the influence of bulk disorder on persistent currents [21]. The bulk disorder was usually considered to be inside the material through which the wave travels. Some general characteristics of persistent current had been obtained in such bulk-disordered systems. It was shown that the typical current in the metallic regime was modified by a corrective diffusive factor and in the localized regime it decreased exponentially with the disorder strength. Due to recent advances in nanotechnology, interestingly, it is possible to fabricate mesoscopic devices in which carriers are mainly scattered by the boundaries and not by impurities or defects located inside them [22]. Based on such an actual structure, recently, a shell-doped nanowire model was proposed, from which a novel transport behavior was obtained, that is, the larger the disorder, the weaker the localization [23]. For the surface roughness or defects, similarly, there may exist a large disorder at the surface of a finite-width ring. Especially, when the system size was shrunk down to the nanometer scale, the surface-to-volume ratio becomes larger, leading to very strong quantum size effects and surface effects.

In a practical implementation of surface roughness, Cuevas et al. [24] had studied the quantum chaotic dynamics by building a new model of quantum chaotic billiard. The essential feature of this model is the inclusion of diagonal disorder at the surface of the system. The obtained energy spectrum statistics shows a complex behavior, very different from that previously reported in the usual chaotic billiard model. Obviously, the similar complex energy spectrum may be expected in a surface disordered ring, indicating some new features in persistent current. How about the influence of the surface disorder on the persistent current in finite-wide rings?

In this paper, taking into account the surface roughness or defects, we build a surface disordered 2D ring model. The effect of surface disorder on persistent current in such 2D ring is explored within the tight-binding frame. It is found that with the increasing disorder strength, the typical current increases in the strong disorder regime, while it decreases in the weak disorder regime. Also, the disorder induced changes in the persistent current depending strongly both on the ring width and radius, which shows up a singular quantum size effect.

2. Model and formulae

We consider a 2D mesoscopic ring enclosing a magnetic flux line. The sample ring can be modeled by M, concentrically connected tight-binding ring chains with N sites each ring chain, as shown in Fig. 1. The maximum number of the open channels in a structure consisting of M ring chains is equal to M. Taking a single atomic level per lattice site, the tight-binding Hamiltonian by considering

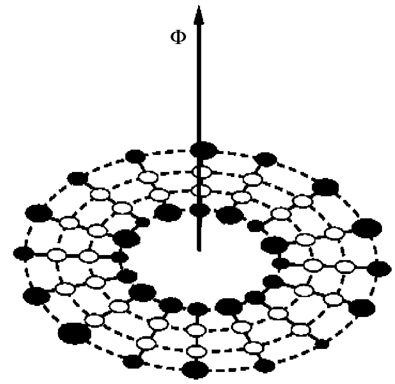

Fig. 1. Schematic illustration of the surface disordered ring with $M = 4$ and $N = 16$. The open circles represent the ordered sites in the core with $\varepsilon_i = 0$, and the solid circles the disordered ones at the surface region with randomly distributed site-energies.

non-interacting electrons is given by

$$H = \sum_i \varepsilon_i c_i^\dagger c_i + \sum_{i,j} V(i,j) c_i^\dagger c_j \tag{1}$$

with on-site energies ε_i, where i labels the coordinates of the sites in the lattice. The hopping integrals $V(i,j)$ are restricted to the nearest neighbors of a site. Assuming that the vector potential A has only an azimuthal component, we take $V(i,j) = t\exp\left(i\int_i^j A\,\mathrm{d}l\right)$, in units of the quantum flux Φ_0, where l is a vector that points from the site i to any of its nearest neighbors. To model the surface disorder, the on-site energies ε_i in the surface region are taken to be randomly distributed within interval $[-W, W]$, W describing the disorder strength, whereas the other sites have a constant energy equal to zero.

For the finite-width ring, we neglect the self-inductance effect on the persistent current in the system. At zero temperature, the total current can be calculated by

$$I = -\partial E/\partial \Phi = -\sum_n \partial E_n/\partial \Phi \tag{2}$$

with E the total energy of the system. Here n labels the corresponding eigenlevels. The second equality in Eq. (2) is valid only in the absence of electron–electron interactions, which are neglected here. The current is a periodic function of Φ with fundamental period Φ_0. Usually, one is interested in the typical current [8,20], which is defined as the square root of the disorder (W) and flux average of the square of the persistent current

$$I_{\text{typ}} = \sqrt{\langle I^2 \rangle_{\Phi,\text{W}}}. \tag{3}$$

To obtain good statistics, the typical currents are averaged over many realizations of the disorder configurations. In our calculations, the number of the averaged configurations varies from 100 to 200, depending on the size of the systems.