Magnetic-flux-induced persistent currents in symmetric-polymer mesoscopic rings


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We investigate magnetic-flux-induced persistent currents in one-dimensional symmetric-polymer (SP) mesoscopic ring, where a defect cluster is embedded into two periodic clusters and the whole cluster possesses mirror symmetry. Under tight-binding approximation, the flux-dependent energy spectra, electronic wave functions, and persistent currents are obtained. It is shown that the energy spectra form band structure and the defect modes appear in the band gap. The persistent current (PC) depends on the magnetic flux, the site energy, and the Fermi level. Particularly, by changing the Fermi level, the SP ring presents metallic and insulative features alternately. Our investigations provide a possible model to explain the anomalously large PC observed in some experiments and contribute to the potential application in quantum-switch devices. © 2006 American Institute of Physics. [DOI: 10.1063/1.2172562]

In mesoscopic systems, one of the quantum effects is the persistent current (PC) in mesoscopic rings threaded by a magnetic flux. This phenomenon was predicted by Büttiker et al.1 in 1983, and there has been a lot of theoretical and experimental work2–6 performed. However, the problem is still not well understood. For example, the experimental observation of Chandrasekhar et al.3 indicated that the current in single Au ring is one or two orders of magnitude larger than the value predicted by the noninteracting theory. Recently more experimental work brought challenges to the theoretical work, such as the sign of the PC near zero field,7 the correlation of the PC with the phase coherence time, etc.8

Generally speaking, the disorder in the system and the electron-electron interaction are two important factors influencing the PC. In this work, we investigate magnetic-flux-induced persistent currents in a one-dimensional (1D) mesoscopic ring, which is constructed according to the symmetric-polymer (SP) model. In a SP model, the defect cluster is embedded into two periodic clusters and the whole cluster possesses mirror symmetry. It is shown that the energy spectra form band structure and the defect modes appear in the band gap. The number of defect modes depends on the number of atoms in the defect cluster. The PC is determined by the magnetic flux, the site energy, and the Fermi level. Particularly, by changing the Fermi level, the SP ring presents metallic and insulative properties alternately. Our investigations provide a possible model to explain the anomalously large PC observed in some experiments and may contribute to the potential application in quantum-switch devices.

We consider the electronic behavior in the 1D SP ring threaded by a magnetic flux. The SP ring contains N sites. Atom A or B occupies the sites according to the sequence \( R(m,n) = (BA)^m B^n (AB)^m \), where \( m \) and \( n \) are the repeating numbers of the units. Obviously, the defect cluster \( B^n \) is embedded into two periodic clusters and the whole cluster possesses mirror symmetry in the SP ring. Under the tight-binding approximation, without the electron-electron interaction, the Schrödinger equation for a spinless electron in a 1D SP mesoscopic ring can be written as

\[
(E - e_l) \psi_l = t_{l,l+1} \psi_{l+1} + t_{l,l-1} \psi_{l-1},
\]

where \( \psi_l \) is the amplitude of wave function on the \( l \)th site index, \( t_{l,l±1} \) is the nearest hopping integral, and the site energy \( e_l \) is taken as \( e_1 = e_A \) or \( e_B \) if atom A (or B) occupies the site. Without loss of generality, we choose the on-site model, for example, \( e_A = -e_B = e \), and \( t_{l,l±1} \) is set as a constant as \( t_{l,l±1} = -1 \). Equation (1) can also be expressed in the matrix form,

\[
\begin{pmatrix}
\psi_{l+1} \\
\psi_l
\end{pmatrix} = T_{l,l+1} \begin{pmatrix}
\psi_{l+1} \\
\psi_l
\end{pmatrix},
\]

where the transfer matrix is

\[
T_{l,l+1} = \begin{pmatrix}
-(E - e_l) & -1 \\
1 & 0
\end{pmatrix}.
\]

Because a magnetic flux \( \Phi \) threaded through the ring will lead to the twisted boundary conditions for the wave functions of the electrons, the equation for the global transfer matrix has the form as

\[
\begin{pmatrix}
\psi_{N+1} \\
\psi_N
\end{pmatrix} = \overline{T} \begin{pmatrix}
\psi_1 \\
\psi_0
\end{pmatrix} = e^{i2\pi \Phi/\Phi_0} \begin{pmatrix}
\psi_1 \\
\psi_0
\end{pmatrix},
\]

where \( \overline{T} = \prod_{l=1}^N T_{l,l+1} \) and \( \Phi_0 = \hbar c/e \) is the flux quantum. By denoting the trace of matrix \( \overline{T} \) as \( \chi = \frac{1}{2} \text{tr} \overline{T} \), the flux-dependent energy spectra of an electron in the mesoscopic ring can be obtained from

\[
\chi = \cos(2\pi \Phi/\Phi_0),
\]

and the persistent current in the ring contributed by the \( n \)th energy level is as follows:

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The flux-dependent energy spectra of several SP rings shows how to observe the large PC in the SP ring. Obviously in each SP ring, the ring behaves like an insulator. Once the Fermi level comes to some special values. In details, the absolute value of $I/I_0$ can be more than 0.4 if the Fermi energy takes some peculiar values [as shown in Figs. 2(a) and 2(b)]. Increasing $\varepsilon$ means that the scattering rate is enhanced and then the dependence of the energy level on the flux becomes smoother. Thereafter the current contribution coming from these energy levels will decrease according to Eq. (6). Consequently, the total current will decrease. Third, at the zero-temperature limit, the sign of the PC is determined by the parity effect. In a ring with an odd number of electrons, the flux-dependent PC is like that in a diamagnet [as shown in Figs. 2(a) and 2(c)]. While in a ring with an even number of electrons, the flux-dependent PC behaves like that in a paramagnet [as shown in Figs. 2(b) and 2(d)]. Finally, the magnitude of PC is also influenced by the electron-filling number $N_e$ or the Fermi level. If the Fermi level is in the energy band, the PC is unsuppressed, while if the Fermi level is around the defect mode in the band gap of energy, the PC is suppressed dramatically. Figures 2(c) and 2(d) show the PC in the ring $R(10, 1)$. It is found that if the filling number of electron is 20 or 21, the Fermi level comes to the defect mode; eventually the PC is suppressed dramatically. In this case the ring behaves like an insulator. Once the Fermi level has a slight deviation to the defect mode, the PC becomes unsuppressed and the ring looks like a metal.

It is worthwhile to show the overall behavior of the PC in the SP mesoscopic ring. Figure 3 plots the PC in several SP rings $R(m, n)$ versus the number of filling electrons $N_e$ when $\Phi/\Phi_0 = -0.252$ and $\varepsilon = 0.5$. Now we are interested in how to observe the large PC in the SP ring. Obviously in each SP ring, the ring can be close to the periodic case when $N_e$ comes to some special values. In details, the absolute value of $I/I_0$ can be more than 0.4 if the Fermi energy takes some peculiar values [as shown in Figs. 3(a)–3(d)]. Here $I_0$ is the maximum of PCs in a periodic structure. In these cases, the PC is absent of suppression, large PC can be observed in the SP ring, and the ring behaves like a metal. On the other
hand, it is also very interesting to observe the dramatically suppressed PC in the SP ring. As shown in Fig. 3, with increasing \( n \) in the SP ring \( R(10,n) \), more and more Fermi energies correspond to the dramatically suppressed PCs. We define \( E_{fc} \) as the Fermi energy corresponding to the dramatically suppressed PC. Around the defect mode, there are two kinds of \( E_{fc} \) in the ring \( R(10,1) \), three kinds of \( E_{fc} \) in the ring \( R(10,7) \), four kinds of \( E_{fc} \) in the ring \( R(10,13) \), and five kinds of \( E_{fc} \) in the ring \( R(10,19) \), respectively. That is to say, at each \( E_{fc} \), the PC is dramatically suppressed and the ring behaves like an insulator. Therefore, by changing the Fermi level, the SP ring presents the features of metallic and insulative properties alternately.

In order to understand the behavior of the PC in the SP ring clearly, the electronic wave function has been studied. Applying Eqs. (2) and (3) in the initial conditions of \( \varphi_0 = 0 \) and \( \psi_1 = 1 \), we have obtained the amplitude of the electronic wave function on each site of the ring. Figure 4 shows the wave function at the Fermi level corresponding to the different highest-occupied electrons in the SP ring \( R(10,19) \), where \( \Phi/\Phi_0 = -0.252 \). It is shown that the wave function is localized when \( \Phi/\Phi_0 = 0 \), \( \Phi/\Phi_0 = 31 \), and \( \Phi/\Phi_0 = 19 \), and five \( \Phi/\Phi_0 \) are intermediated when \( \Phi/\Phi_0 = 25 \) and \( \Phi/\Phi_0 = 35 \). We observe a similar metallic-insulative transition in the SP ring.

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