行政院國家科學委員會專題研究計畫成果報告

中觀系統的量子傳輸 II: [一]中觀常態結構 [二]中觀超導結構
Quantum transport in mesoscopic systems II: [1] Mesoscopic normal structures [2] Mesoscopic superconducting structures

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一、中文摘要

我們探討了中觀系統內的時變量子傳輸特性。所探討的系統包括: 量子接點、中觀導電環、雙位壘結構、量子阱結構、以及 SNS 接頭。

對於量子接點，我們考慮了有橫向偏振時變電磁場作用時的傳輸特性。此時變場引起的非彈性散射，使得傳輸電子可以作次能帶間及側能帶間的躍遷到次能帶底，而使直流電導 G 產生急降形抑制特性。我們提出了可行的實驗裝置來探討這些特性。此外，我們也對於先前的工作—縱向偏振時變電磁場，提出了可行的實驗裝置。

對於中觀導電環，我們也探討了當穿過的磁通量隨時間線性增加時，雜質對耗散特性的影響。在弱雜質範圍，可區分成二種不同的耗散特性。這二種耗散特性對應於電子從非彈性散射流出時，有機會或是無法到達古典迴轉點。當雜質變強時，環內感應電流的直流分量與能量的關係，顯示出較強的振盪；這些振盪現象與一維晶格的能帶結構密切相關。我們的結果提供一個合理的理論架構，用以描述從費米面重要範圍（強雜質）到遠低於費米面的電子態之貢獻重要時（弱雜質）的連續轉變。

我們探討了一個有限範圍的時變電位作用在雙位壘結構的量子傳輸現象。由位壘的寬度所決定，使電導 G 產生兩組不同的結構—當$\mu=m\hbar\omega$時，或者是當$\mu=E_b\pm m\hbar\omega$時。並且，對於後者，我們也得到 Wagner 所發現的共振傳輸湮滅，但做了一點定量修正。

對於量子阱結構內量子傳輸的時變效應，我們發現當μ比阱內的束縛態能量高出$m\hbar\omega$時，直流電導 G 產生 Fano 結構。當時變電位的振幅增加時，這些 Fano 結構變寬，同時也出現較高$m\hbar\omega$的散射過程。這些特性即為准束縛態的形成。

我們繼續之前對 SNS 接頭時變特性的研究，探討 SNS 接頭內，時變電位對於電流—相位關係的效應。我們已得到更深層的物理意義。傳輸的準粒子可以藉由放出$m\hbar\omega$的能量，暫時被捕捉在 Andreev 能級。這些被捕捉的準粒子仍對超導電流有貢獻，直到它們被再次激發離開 Andreev 能級而又回到端電極。雖然這些捕捉過程在整個超導相位差的範圍中都有貢獻，但較深的 Andreev 能級因為寬度較細以致仍能對 SNS 接頭的電流—相位關係做成顯著的特性。

最後，我們也對具有“寬－窄－寬”結構的接頭之時變傳輸特性作了初步探討。而且也探討了局部密度近似（Local Density Approximation, LDA）的圖像，以便將來應用在我們有興趣的系統。

關鍵詞：量子傳輸，量子接點，中觀導電環，次能帶間的躍遷，側能帶間的躍遷，Fano 結構，Andreev 能階。

Abstract

We have studied the time-dependent quantum transport characteristics in mesoscopic systems (MS) including quantum point contacts (QPC), mesoscopic conducting rings, double-barrier structures, quantum well structures, and SNS junctions.

For a QPC, we have considered its transport characteristics in the presence of a transversely polarized electromagnetic field. The inelastic scattering that causes the transmitting electrons to make inter-subband and inter-sideband transitions to a subband bottom gives rise to dip-like suppressed features in the dc conductance G. We have proposed an experimental setup for the observation of the features found in this investigation. We have also proposed another experimental setup for the observation of findings in our previous investigation – when the electromagnetic field considered is longitudinally polarized.

The effects of impurities on the dissipation characteristics of a mesoscopic conducting ring has been studied for the case when the threading magnetic flux is increasing linearly with time. In the weak impurity regime, two different dissipation characteristics are identified. These two regimes correspond to situations when the electrons that emanate out of incoherent scatterings have, or does not have, appreciable chance of reaching their classical turning point. As the impurity becomes stronger, the dc component of the induced current in the ring shows

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strong oscillatory dependences to the chemical potential. These oscillatory behaviors are found to associate closely with the band-structure of a one-dimension crystal. Our results thus provide a consistent theoretical framework describing the continuous cross-over from the Fermi surface dominated (strong impurity) regime to the regime (weak impurity) when contributions from states far below the Fermi surface are important.

We have studied the quantum transport phenomena in a double-barrier structure acted upon by a finite-range time-modulated potential. Depending on the width of the barrier, two possible sets of structures in G can occur, either when $\mu = m\hbar\omega$ or when $\mu = E_b \pm m\hbar\omega$. Furthermore, for the latter case, we also obtain the quenching of the resonant transmission found by Wagner, but with a small quantitative modification.

For the effects of a time-modulated potential on the transport through a quantum well, we find in the dc conductance G Fano-structures when μ is at $m\hbar\omega$ above the bound state energy in the well. These Fano-structures are broadened, together with the emergence of higher $m\hbar\omega$ processes, as the amplitude of the time-modulated potential increases. These features are identified as the formation of quasi-bound states.

We have continued our investigation of the effects of a time-modulated potential on the current-phase relation of a super-conductor-normal-metal-superconductor (SNS) junction. A deeper physical understanding has been obtained. The transmitting quasi-particles can be trapped temporarily into an Andreev level by emitting $m\hbar\omega$. These trapped quasi-particles will continue their contribution to the supercurrent until they are re-excited out of the Andreev level and back into the end-electrodes. Even though these trapping processes contribute over the entire range of the superconducting phase difference ϕ, the deeper Andreev level is sharp enough so as to give rise to robust characteristics in the current-phase relation of the junction.

Finally, we have done preliminary exploration on the time-modulated transport characteristics through junctions that has wide-narrow-wide configurations. We have also explored the local-density approximation scheme that will be applied to the systems of our interest.

Keywords: quantum transport, quantum point contact, mesoscopic ring, inter-subband transition, inter-sideband transition, Fano structures, Andreev levels.

二、Motivations and goals

Mesoscopic systems [1-2] are of great importance due to their potential technological applications and due to the unique set of physical phenomena they exhibit. More recently, the time-dependent phenomena in mesoscopic systems have attracted much attention.[3-12] It is because the time-dependent phenomena could probe deeper into the dynamical aspect of the physics of the systems. In addition, the effects of photons on electron transport is of practical importance.

In our previous studies on the transport characteristics in narrow constrictions, we found that the one-dimensional subband structures support the existence of quasi-bound states (QBS).[13] These QBS are formed at energies just below a subband bottom. The finite number of subbands in the system and the tunability of the dimension of such system together substantiate the significance of the QBS. It is a key factor for the quantum transport phenomena in mesoscopic systems. Thus we opt in this project to investigate the various manifestation of the QBS features in the time-dependent transport phenomena.

The time-dependent fields we considered include gate-potentials, and transversely polarized electromagnetic fields. We compare the characteristics due to QBS formed just below a subband bottom, as in the cases of QPCs; or QBS formed from resonant states, as in the case of a double-barrier structures; and QBS formed from true bound states, as in the case of a quantum well, or a SNS junction. Through these studies, we aim to establish a general picture for the QBS features.

Another reason that makes mesoscopic physics of fundamental interest is that it allows the issue of decoherence to be studied experimentally. This is essentially why that a mesoscopic conducting ring acquires its importance and attentions in the recent past. [14-17] Most of the theoretical discussions and predictions for the properties of such a mesoscopic ring, threaded by a magnetic flux that changes linearly in time, have assumed an adiabatic picture, that is, describing the time-evoluation of the quantum states in terms of the instantaneous eigen-states of the system. We feel that the time-evolution of the states should be treated more carefully. Furthermore, the incoherent processes were essentially described in terms of relaxation times. This relaxation-time approach, however, cannot naturally re-introduce those electrons suffered from incoherent scattering back to the system. Therefore we choose to bring to this problem our insight obtained from studies in time-dependent phenomena of other mesoscopic systems. Our purpose is to help establish a sound theoretical basis for the study of mesoscopic rings and to clarify some of the recent controversies among researchers.

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三、Results and discussions

The effect of a transversely polarized electromagnetic field on the transport characteristics of a QPC is studied using a generalized scattering-matrix method, which has incorporated a time-dependent mode-matching scheme. The transverse field induces coherent inelastic scatterings that include both intersubband and intersideband transitions. These scatterings give rise to the dc conductance G a general suppressed feature that escalates with the chemical potential. In addition, particular suppressed features--the dip structures -- are found in G. These features are recognized as the quasi-bound-state (QBS) features that arise from electrons making intersubband transitions to the vicinity of a subband bottom. For the case of larger field intensities, the QBS features that involve more photons are more evident. These QBS features are closely associated with the singular density of states at the subband bottoms.

For the observation of these features, one must be careful about the bolometric effect, especially in the end-electrode regions. Therefore the end-electrodes have to be kept out from the time-modulated field. Hence we propose to generate the transversely polarized field by biasing the split-gates with an ac bias source. The split-gates are also negatively biased in order to define the QPC electrostatically. For the ac bias source, if the frequency is of order 10GHz, devices such as IMPATT diodes is available.

In the case of a mesoscopic ring, two dissipation characteristics are obtained when the impurity is weak. The first regime corresponds to the situation when the electrons that emanate out of incoherent scatterings, and move along the direction of the induced electric field, have appreciable chance of reaching their classical turning point. In this regime, the dissipation is not Ohmic-like and the dc current component in the ring increases with the Fermi energy. In the second regime, most of the electrons that emanate out of incoherent scatterings, and move along the direction of the induced electric field, have negligible chance of reaching their classical turning point. In this regime, the dissipation is Ohmic-like while the dc current component becomes independent of the Fermi energy. However, in this latter regime, we find that the ac current component, with a period of $1/\omega$, in the ring is the same as the adiabatic result. When the impurity is strong, the dc component of the current shows strong oscillatory behavior with respect to the Fermi energy. This can be understood from the one-dimensional band structure.

In a double-barrier structure, we consider the effects of a time-modulated potential. When the barrier width L is small such that the resonant level is poorly defined, we fine that there are dip structures in G at the energies $\mu = m\hbar\omega$. However, when L is very large such that the resonant levels are very well defined, there are additional peak in G at energies $\mu = E_b + m\hbar\omega$. The cross-over between these two limiting regimes, with intermediate Ls, show structures at all these incident energies. Our results show the competitive in the formation of QBS. Also in looking for the quenching structures in the resonant peak, we find that the quenching effect occurs only for sufficiently sharp resonance peak.

In a quantum well structure, we consider the effects of a time-modulated potential when the transport is parallel with the well width. The transmitting electrons can be trapped by the bound states in the well if their incident energy is at $m\hbar\omega$ away from the bound state energies. This trapping process gives rise to Fano-structures in the dc conductance G. The evolution of the G-structure from the Fano-like to the dip-like structure is studied when the position of the time-modulated potential is changed. Our results show that the dip structure is the more robust structure indicating the existence of QBS, even though in principle we should go after the peak, or the pole in G.

In a SNS junction, and in the presence of a time-modulated potential in the normal region, the current-phase relation shows dip structures that are found to originate from the trapping of the transmitting quasi-particles by the deeper Andreev levels in the junction. The trapping in the shallower Andreev level does contribute but cannot give rise to sharp characteristics. Because its contribution is spread over a wide $\Delta\phi$ range.

四、Self-evaluation of project results

In this project, we have studied the time-dependent quantum transport in various mesoscopic systems. New understanding has been obtained about the importance and the manifestation of the trapping process. Part of these results have been presented in the 1999 annual meeting of the Physical Society of the Republic of China.[18] Two papers are published in the Chinese Journal of Physics, and four more papers are either being submitted or to be submitted.[19] The issues studied are of current interest to the mesoscopic communities and the results obtained are of importance to the further development of the field.

五、參考文獻

[1] D.K. Ferry and S.M. Goodnick, *Transport in Nanostructures* (Cambridge University

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Press, Cambridge, U.K., 1997).
[2] Y. Imry, *Introduction to Mesoscopic Physics* (Oxford University Press, Oxford, U.K., 1997).
[3] F. Hekking and Y.V. Nazarov, Phys. Rev. B **44**, 11506 (1991).
[4] P.F. Bagwell and R.K. Lake, Phys. Rev. B **46**, 15329 (1992).
[5] Q. Hu, Appl. Phys. Lett. **62**, 837 (1993).
[6] R.A. Wyss, *et al.*, Appl. Phys. Lett. **63**, 1522 (1993).
[7] L.Y. Gorelik, *et al.*, Phys. Rev. Lett. **73**, 2260 (1994).
[8] C.S. Chu and C.S. Tang, Solid State Commun. **97**, 119 (1996).
[9] C.S. Tang and C.S. Chu, Phys. Rev. B **53**, 4838 (1996).
[10] K. Yakubo, *et al.*, Phys. Rev.l B **54**, 7987 (1996).
[11] C.S. Tang and C.S. Chu, Physica B **254**, 178 (1998).
[12] C.S. Tang and C.S. Chu, Phys. Rev. B **60**, 1830 (1999).
[13] C.S. Chu and M.H. Chou, Phys. Rev. B **50**, 14212 (1994).
[14] M. Buttiker, Phys. Rev. B **32**, 1846 (1985)
[15] M. Buttiker, Y. Imry, and R. Landauer, Phys. Lett. **96A**, 365 (1983).
[16] Y. Gefen and D. Thouless, Phys. Rev. Lett. **59**, 1752 (1987).
[17] L. Gorelik, *et al.*, Phys. Rev. Lett. **78**, 2196 (1997).

[18] *Conference papers:*
The 1999 annual meeting of the Physical Society of the Republic of China

H.C. Liang and C.S. Chu, "Effects of incoherent processes on the quantum transport through a finite-range time-modulated potential."
Oral session: Da4

C.S. Tang and C.S. Chu, "Time-modulated effects in a narrow constriction: from photon-induced transport to ac response"
Oral session: Da5

M.T. Liu and C.S. Chu, "Effects of incoherent processes on the dc current induced by a linearly time-dependent ring"
Oral session: Da6

[19] *Published and submitted papers:*

C.S. Chu and H.C. Liang, 1999, "Quantum transport in a double-barrier structure in the presence of a finite-range time-modulated potential"
Chin. J. Phys. **37**, 411 (1999)

C.S. Chu and H.C. Liang, 1999, "Quantum transport through a quantum well in the presence of a finite-range time-modulated potential"
Chin. J. Phys. **37**, 509 (1999)

M.T. Liu and C.S. Chu, 1999, "Dissipation in a partially coherent flux-driven ring"
(submitted)

C.S. Tang and C.S. Chu, 1999, "Coherent quantum transport in the presence of a finite-range transversely polarized time-dependent field"
(submitted)

M.T. Liu and C.S. Chu, 1999, "Effects of an impurity on the dissipation of a mesoscopic ring"
(submitted)

H.C. Liang and C.S. Chu, 1999, "Current-phase relation of a SNS junction in the presence of a time-modulated potential"
(submitted)

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