行政院國家科學委員會補助專題研究計畫成果報告

※※※※※※※※※※※※※※※※※※※※※※※※※
※　　　　　　　　　　　　　　　　　　　　　　　　※
※　　中觀系統的傳輸特性及量子傳輸理論之研究　　※
※　　　　　　　　　　　　　　　　　　　　　　　　※
※※※※※※※※※※※※※※※※※※※※※※※※※

計畫類別：■個別型計畫　　□整合型計畫
計畫編號：NSC 89－2112－M－009－074－
執行期間：88 年 8 月 1 日至 90 年 7 月 31 日

計畫主持人：朱仲夏

本成果報告包括以下應繳交之附件：
- □赴國外出差或研習心得報告一份
- □赴大陸地區出差或研習心得報告一份
- ■出席國際學術會議心得報告及發表之論文各一份
- □國際合作研究計畫國外研究報告書一份

執行單位：國立交通大學電子物理系

中　華　民　國　　90 年　10 月　30 日

行政院國家科學委員會專題研究計畫成果報告

中觀系統的傳輸特性及量子傳輸理論之研究
A study on the transport characteristics in mesoscopic systems and the quantum transport theory

計畫編號：NSC 89-2112-M-009-003
執行期限：88 年 8 月 1 日至 90 年 7 月 31 日

主持人： 朱仲夏 國立交通大學電子物理系
計畫參與人員：唐志雄 東南技術學院電子工程系
柳銘哲 國立交通大學電子物理系
梁輝正 國立交通大學電子物理系
陳毓豪 國立交通大學電子物理系
賴良星, 蘇俊鐘, 沈士文
國立交通大學電子物理系

一、中文摘要

在本計畫中 我們研究了(1)開放量子點的量子傳輸特性 包括有外加時變電場的情形;(2)介觀導環在時變磁場下的非絕熱耗散特性;(3)峽窄通道中的非絕熱抽運現象;以及(4)磁雜質的失相效應。

在開放型的量子點方面 我們考慮了與量子點兩個開口位置有關的對稱與不對稱的情況。我們發現當穿透電子能量與量子點中準束縛態的電導就顯出急降形(或 Fano)結構 我們[illegible]此時電子停留在點中[illegible]究結果得出時變的位能[illegible]是產生邊能帶間[illegible]電導[illegible]產生更多急降形結構。

在介觀導環的非絕熱耗散特性方面 我們考慮了導環上有雜質的情況 穿過導環的磁場隨時間線性增加 也推動環中電流 而其特性主要[illegible]就是電子是否能夠[illegible]間到達其古典迴轉點[illegible]就產生了歐姆(Ohmic)或非歐姆(non-Ohmic)特性。在強雜質放範疇時 多重散射造成多個迴轉點 使得環中的 dc 電流在能量上有振盪的表現。

在非絕熱抽運現象方面 我們考慮了在空間與時間上都有週期性變化的位能所引起的現象 其空間[illegible]分別以 K 與 Ω 來表示。這裡的抽運現象是不需要依靠系統的結構 單抽運位能的相速度就可以產生抽運的效果。當頻率為零時[illegible]穿透係數有谷形結構的週期性。這些結構在 Ω 為有限時[illegible]然明顯[illegible]量則偏移了約 $h\Omega/2$ 偏移的方向是與抽運位能的相速度方向和電子的穿透方向有關 這因此造成穿透係[illegible]性 造成抽運電流的產生。我們針對此抽運現象 提出一個可[illegible]

在辨識磁性雜質的[illegible]效[illegible]們考慮了雜質位在兩個位壘中的情形。雜質的局域磁矩與在穿透中電子的自旋發生作用 電子[illegible]失相[illegible]的[illegible]過程[illegible]而是電子與其環境[illegible]局域磁矩。[illegible]生[illegible]作用[illegible]成功的找到此問題的精[illegible]所有電子與失相源纏磁性雜質的可能過程。我們探討失相源導致失相的能力 是依據電子[illegible]值為一的程度來討論。我們也提出了一個描述局域失相源的 S 矩陣模型 此[illegible]

有同調反射的可能 S 矩陣模型提出一個微觀的基礎。

關鍵詞：量子傳輸　開放型的量子點　介觀導環　抽運　非絕熱　邊能帶　共振耦合　Fano 結構　　失

Abstract

We have studied (1) the quantum transport characteristics of open quantum dots with or without the presence of an external time-modulated fields; (2) the non-adiabatic dissipation characteristics in a mesoscopic ring threaded by a time-dependent magnetic flux; (3) the non-adiabatic quantum pumping phenomena in a narrow channel; and (4) the dephasing effects of a magnetic impurity.

For the open quantum dots, we have considered symmetric and asymmetric dots, as far as the positions and the alignment of the two dot openings are concerned. We find that the dc conductance G exhibits dip structures or Fano profiles whenever transmitting electrons have energies coincide with that of the quasi-bound states formed inside the dot. The dwell-time of these electrons in the dot has also been studied. The effect of a time-modulated potential in the dot is to give rise to inter-side-band transitions and to more dip structures in G.

For the non-adiabatic dissipation characteristics in a mesoscopic ring, we have considered a ring that contains an impurity. The ring is driven by a threading magnetic flux that changes linearly with time. The characteristics are governed by the fate of the electrons whether they can or cannot encounter their classical turning point in between two incoherent processes. In the weak impurity regime, this gives rise to either Ohmic or non-Ohmic behavior. In the strong impurity regime, multiple scatterings give rise to many turning points and, subsequently, to the oscillatory behavior in the energy dependence of the dc current in the ring.

For the non-adiabatic quantum pumping, we have considered phenomena induced by a potential that has both spatial and temporal periodicity characterized, respectively, by K and $\boldsymbol{\Omega}$. These pumping phenomena do not require an asymmetry in the system configuration. The phase velocity of the pumping potential alone is sufficient to cause the pumping. We find, in the zero frequency limit, the transmission exhibits valley structures a consequence of the K periodicity. These valley structures remain robust in the regime of finite $\boldsymbol{\Omega}$, while their energies of occurrence are shifted by about $h\boldsymbol{\Omega}/2$. The directions of these energy shifts depend on the directions of both the phase-velocity of the pumping potential and the transmitting electrons. This gives rise to both the asymmetry in the transmission coefficients and the pumping current. We have proposed an experimental setup for the observation of our predicted phenomena.

To identify the dephasing effect of a magnetic impurity, we have considered locating such an impurity in between two barriers. The local moment of the magnetic impurity interacts with the spin of the transmitting electrons. The dephasing process studied is not resulted from inelastic scattering. Rather, it is resulted from the interaction of the electrons with the degree of freedom of their environment the local moment of the magnetic impurity. We have solved the problem exactly, including all possible entanglement of a transmitting electron with the dephasor the magnetic impurity. The dephasing power of the dephasor has been investigated by exploring the deviation from unity of the resonant transmission. A S-matrix model is proposed for the description of a local dephasor that has coherent reflection. Our study provides a microscopic basis for such a S-matrix model.

Keywords: quantum transport, open quantum dot, mesoscopic ring, quantum pumping, non-adiabatic, side-band, resonant coupling, Fano structures, dephasor

二、緣由與目的

Mesoscopic systems [1-2] are of great importance due to their potential technological applications and to the unique set of physical phenomena they exhibit. More recently, time-dependent phenomena [3-12] and the dissipation, or dephasing, phenomena [13-16]in mesoscopic systems have attracted much attention. The time-dependent phenomena could probe deeper into the dynamical aspect of the physics in the systems, and the effects of photons on electron transport is of practical importance. On the other hand, the dissipation and the dephasing phenomena, together with their physical implications, are intimately connected to our understanding of the physical states of electronic systems at zero temperature. More interestingly, on a broader scope, the time-dependent and the dephasing phenomena could also be connected in an intricate way.

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).[17] The finite number of subbands in the system and the tenability of the dimension of such system together help to enhance the significance of the QBS as a key characterization factor for the mesoscopic structures.

Meanwhile, the transport characteristics of quantum dots have attracted much research attentions. These characteristics include coulomb blockade, Kondo effects, possible spin dynamics, scarring of the wavefunctions inside the dots, and connection between quantum and classical chaos.[18-19] Since it is expected that the coulomb blockade becomes negligible for open quantum dots, then it might be easier to probe the energy levels in the dots via transport measurement. Therefore, in this project, we opt to investigate the possible QBS formed in the open quantum dots with or without the presence of an external time-modulated potential.

Another reason that causes mesoscopic physics of fundamental interest is that it allows issues of decoherence to be studied experimentally. This is essentially why that a mesoscopic conducting ring acquires its importance and attentions from the mesoscopic community in the recent past.[20-23] 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. Essentially, the time-evolution of the quantum states are described in terms of the instantaneous eigenstates of the system. We feel that the time-evolution of the states should be treated more carefully. Furthermore, the incoherent processes were treated within a relaxation time approach. Again, we do not feel comfortable with such treatment. The major reason of our objection is that the relaxation time approach cannot naturally reintroduce those electrons suffered from incoherent scatterings back into the system.

In our previous study, we have remedied these shortcomings by adopting a S-matrix model, proposed initially by Buttiker for incoherent scatterings,[24] for our time-dependent situation in a ballistic mesoscopic ring.[16] This allows us to treat both the incoherent scatterings and the coherent inelastic processes non-perturbatively and on the same footing. We find two interesting dissipation characteristics. It is therefore of great interest to investigate the non-ballistic mesoscopic ring case. Thus, in this project, we investigate the dissipation characteristics of a mesoscopic ring that consists of an impurity.

The phenomenon of adiabatic quantum pumping in mesoscopic systems has attracted much attention since the first proposal by Thouless.[25] The pumping phenomena refer to net transport of charges at zero bias. Mechanisms giving rise to quantum pumping involves cyclic deformations of more than one parameter in the system. The adiabatic deformation causes the transformation of a finite amount of charges in one deformation cycle. Thus far, most of the studies have concentrated on the adiabatic regime. It is legitimate then to explore the nonadiabatic aspect of the pumping phenomena. Besides, we have considered, in this project, another type of pumping mechanism that the pumping potential has a definite phase velocity. Our interest is to see how such phase velocity help carry, or pump, electrons across the structures.

The issue of dephasing at zero temperature has caused heated debate among forefront researchers in the condensed matter community. Is the dephasing extrinsic? Does its sole existence depend on the presence of dephasing agents such as magnetic impurities? Or if the dephasing were intrinsic, what would be the dephasing mechanism? There are a number of proposals on the dephasing mechanisms but no consensus has yet been reached. Candidates for such dephasing mechanisms must be elastic scatterings, or at least very nearly so.

Stern *et al* [13] had presented their case convincingly that dephasing can occur in elastic scatterings, as long as the scattering electrons can couple to the internal degrees of freedom of the dephasor. However, in their analysis, they had neglected the coherent backscattering effects. Thus a lot of possible entanglements between the electrons and the dephasor have not been accounted for. How would these affect the dephasing scenario? Hence in this project, we explore this interesting issue by considering a problem of similar nature but keeping all the multiple scattering processes. We attempt to extract information about the dephasing from the transmission coefficients.

三、結果與討論

In an open quantum dot, we extend our mode-matching method to this case when the transverse dimension varies along the propagation direction. The efficiency and the convergence property has been checked with satisfactory outcome.

We have calculated the conductance G, the dewell time of the transmitting electrons in the dots, and the spatial profile of the wavefunction. Suppressed features in G are found, including both dip and Fano structures, as the incident energies line up with the particle-in-a-box energy levels in the dot. The correspondence remains surprisingly well even for dots with large openings dot opening width is one half that of the dot width. On the other hand, not all the particle-in-a-box levels show up in the suppressed features in G. Furthermore, the correspondence starts to deteriorate as the chemical potential increases. As for the dewell time, the width of the G structures correspond quite well with the dewell time of the particle in the dot. A narrower G structure corresponds to a longer dewell time. But if the G structure becomes so narrow, we find that the particle will simply suffer total reflection. Concerning the symmetry of the dot, some of the particle-in-a-box levels do not show up in G for symmetry dots because the symmetry forbade some transitions to occur. This is confirmed in the case of asymmetric dots. Those previously missing structures show up in G.

In the case of a mesoscopic ring, and when the impurity is weak, two dissipation characteristics are obtained. The first regime the Non-Ohmic regime has the dc component in the current increases with the Fermi energy. This corresponds to the situation when electrons that emanate out of incoherent scatterings can reach their classical turning point. The second regime the Ohmic regime has the dc current independent of the Fermi energy. This corresponds to the situation when most of the electrons that emanate out of incoherent scatterings, and move along the direction of the induced electric field, are not able to reach their classical turning point. On the other hand, when the impurity is strong, we show that the impurities have brought forth multiple forbidden regions, or multiple turning points, to the electrons. The dc current exhibits finger-like structures with the minima drop to zero.

In the case of the nonadiabatic quantum pumping, we have proposed and analyzed in detail a mechanism. The pumping mechanism is due to the resonant coupling of the electron with the pumping potential that has both spatial and temporal periodicity. We have calculated the transmission coefficients for electrons incident from both left and right side of the narrow channel. These coefficients have valley structures which depends on both the direction of the incident electron as well as the phase velocity direction of the pumping potential. These valley structures and the asymmetry in the transmission coefficients are the key findings in this work. A two-component approximation for the wavefunction has been proposed to help demonstrate the resonant coupling nature of our findings. The demonstration has been very successful. We have also calculated the differential current for the zero source-drain biased channel. Major features found are alternate valley and broad peak structures. Our finding is in sharp contrast to the pumping effect in the incoherent regime. [26] An experimental setup has been proposed for the possible realization of the pumping mechanism in this work.

In the dephasing power of a magnetic impurity, we have calculated the transmission coefficients for an electron transmitting through a double barrier structures in which the impurity is located. The resonant transmission occurs at the maxima of the transmission coefficients T. In the absence of the magnetic impurity, the value of T=1 for the resonant transmissions. The resonant T=1 also for the case when the impurity is a normal impurity, without a local magnetic moment. But for the case a magnetic impurity, the resonant T drops with the strength of the impurity, showing the dephasing effect of the magnetic impurity. We also keep track of the resonant transmission for a given magnetic impurity strength while increasing the barrier height. The resonant transmission drops also with the height of the two barriers. This can be understood from the fact that a higher barrier height traps the transmitting electrons longer in between the two barriers and hence amplifies the cts of the magnetic impurity. This shows that we cannot talk about the dephasing power of a magnetic impurity without mentioning the environment in which it is located. Finally, we can relate this system to a S-matrix model that is meant to describe a local incoherent scatterer that allows coherent backscatterings. As such, we have attempted to provide a microscopic basis for the S-matrix model proposed by Buttiker. [20]

四、計畫成果自評

In this project, we have found new features and understandings in the quantum transport characteristics of open quantum dots and mesoscopic rings. We have also proposed a new nonadiabatic quantum pumping mechanism as well as its possible observation. Finally, we have explored in detail the dephasing effects of a magnetic impurity. Part of these results have been published in two papers in refereed journals.[27] Part of these results have been presented in the 2000 and 2001 annual meeting of the Physical Society of the Republic of China, in the 2000 APS March meeting, and in the Advanced Hetero-structure Workshop 2000. [28] Two papers are in preparation. The results obtained in this project should have impact and interest to the mesoscopic communities.

五、參考文獻

[1] D.K. Ferry and S.M.Goodnick, *Transport in Nanostructures* (Cambridge University 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. 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] A. Stern, Y. Aharonov, Y. Imry, Phys. Rev. A **41**, 3436 (1990)

[14] P.A. Mello, Y. Imry, and B. Shapiro, Phys. Rev. B **61**, 16570 (2000)

[15] A. Silva and S. Levit, cond-mat/0101081 (2001)

[16] M. T. Liu and C.S. Chu, Phys. Rev. B **61**, 7645 (2000)

[17] C.S. Chu and M.H. Chou, Phys. Rev. B **50**, 14212 (1994)

[18] D. Goldhaber-Gordon *et al.*, Nature **391**, 156 (1998)

[19] J.P. Bird *et al.*, Phys. Rev. Lett. **82**, 4691 (1999)

[20] M. Buttiker, Phys. Rev. B **32**, 1846 (1985)

[21] M. Buttiker, Y. Imry, and R. Landauer, Phys. Lett. **96A**, 365 (1983)

[22] Y. Gefen and D. Thouless, Phys. Rev. Lett. **59**, 1752 (1987)

[23] L. Gorelik, *et al.*, Phys. Rev. Lett. **78**, 2196 (1997)

[24] M. Buttiker, Phys. Rev. B **32**, 1846 (1985)

[25] D.J. Thouless, Phys. Rev. B **27**, 6083 (1983)

[26] O. Entin-Wohlman, Y. Levinson, Y.M. Galperin, Phys. Rev. B **62**, 7283 (2000)

[27] Published papers:

“Effects of an impurity on the dissipation in a partially coherent flux-driven ring”
M.T. Liu and C.S. Chu, Solid State Commun. **11**, 167 (2000)

“Nonadiabatic quantum pumping in mesoscopic nanostructures”
C.S. Tang and C.S. Chu, Solid State Commun. **129**, 353 (2001)

[28] Conference papers:

The 2000 annual meeting of the Physical Society of the Republic of China

C.S. Chu and M.T. Liu
“Ohmic and non-Ohmic behavior in a partially coherent flux-driven conducting ring”
Oral session: Da1, Da2

Y.H. Tan, C.S. Tang, and C.S. Chu
“Quantum transport as a probe to the quasibound states in the cavity of a ballistic electron waveguide”
Poster session: PN4

L.S. Lai, C.S. Tang, and C.S. Chu
“Effects of an asymmetric barrier on the conductance of a narrow constriction”
Poster session: PN5

The 2000 APS March meeting

C.S. Chu and M.T. Liu
“Dissipation in a partially coherent flux-driven ring”
Oral session: I26.4

Advanced Heterostructure Workshop 2000

C.S. Chu
“Coherent quantum transport in narrow constrictions in the presence of a transversely polarized time-dependent field”

The 2001 annual meeting of the Physical Society of the Republic of China

M.T. Liu and C.S. Chu
“Dephasing effects in nanostructures”

C.S. Tang and C.S. Chu
“New mechanism of quantum pumping in mesoscopic structures”