行政院國家科學委員會專題研究計畫　期中進度報告

介觀物理系統在光子晶體中的量子散粒雜訊(1/2)

計畫類別：個別型計畫
計畫編號：NSC93-2112-M-009-037-
執行期間：93 年 08 月 01 日至 94 年 07 月 31 日
執行單位：國立交通大學電子物理學系(所)

計畫主持人：陳岳男
共同主持人：鄭舜仁

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 94 年 5 月 18 日

行政院國家科學委員會補助專題研究計畫期中進度報告

介觀物理系統在光子晶體中的量子散粒雜訊(1/2)

計畫類別：☐ 個別型計畫　　☐ 整合型計畫
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計畫主持人：陳岳男
共同主持人：鄭舜仁
計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：☐精簡報告　☐完整報告

本成果報告包括以下應繳交之附件：
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☐出席國際學術會議心得報告及發表之論文各一份
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執行單位：交通大學電子物理系

中　華　民　國　94 年　5 月　31 日

1. 中文摘要

在執行將近一年的的研究計畫後，已獲致不錯的成果：首先，我們已先算出由微型共振腔所包夾之量子環 p-i-n junction 的量子散粒雜訊，除了發現到藉由觀測量子散粒雜訊可以反應量子環激子在共振腔的自發輻射特性，也可以得到傳統量測直流電所得不到的資訊。我們更將此一方法推廣到量子點 p-i-n junction 在 one-band 或是 two-band 光子晶體中的情形，也同樣可以反應光子晶體能隙(photonic band gap)的特性，值得一提的是將 p-i-n junction 與光子晶體光學性質的結合，有可能在這樣的元件中製造出量子糾纏態與完成所謂的量子隱形傳輸(quantum teleportation)。在第一年計畫的資助下，已發表一篇期刊、一篇即將出刊(收錄在書中)的邀搞文章，以及 3 篇送出審查中的文章。

2. Abstract

Shot-noise spectrum of quantum ring (QR) excitons in a *p-i-n* junction surrounded by a microcavity is derived analytically. Radiative decay properity of a QR exciton can be obtained from the observation of the current noise, which also gives the extra information about the tunnel barriers. Different noise feature between the quantum dot (QD) and QR is pointed out, and may be observed in a suitably designed experiment. Furthermore, we have also investigated the shot-noise spectrum of a quantum dot *p-i-n* junction embedded inside a three-dimensional photonic crystal is investigated. The characteristic of the photonic band gap is revealed in the current noise with discontinuous behavior. Applications of such a device in entanglement generation and quantum teleportation are pointed out, and may be achieved with current technologies.

3. Contents

I. Current noise of quantum ring excitons incorporated inside a *p-i-n* junction

We have considered a QR embedded in a p-i-n junction as shown in Fig. 1. Both the hole and electron reservoirs are assumed to be in thermal equilibrium. For the physical phenomena we are interested in, the fermi level of the *p* (*n*)-side hole (electron) is slightly lower (higher) than the hole (electron) subband in the dot. After a hole is injected into the hole subband in the QR, the *n*-side electron can tunnel into the exciton level because of the Coulomb interaction between the electron and hole.

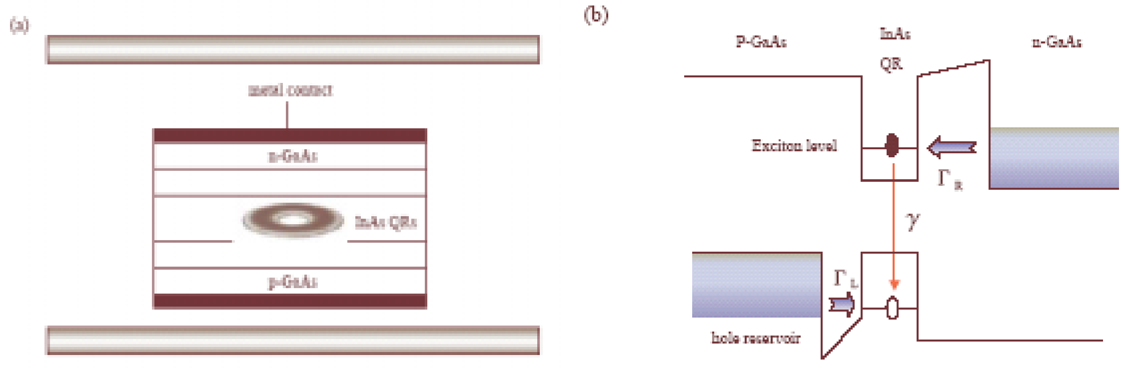

Fig.1 (a) Schematic description of a QR inside a p-i-n junction surrounded by a planar microcavity *with length L. (b) Energy-band diagram of a QR in the p-i-n junction.*

By applying the master equation technique and the MacDonald formula, the noise spectrum can be obtained. The zero-frequency noise (Fano factor) as a function of cavity length is given in Fig.2.

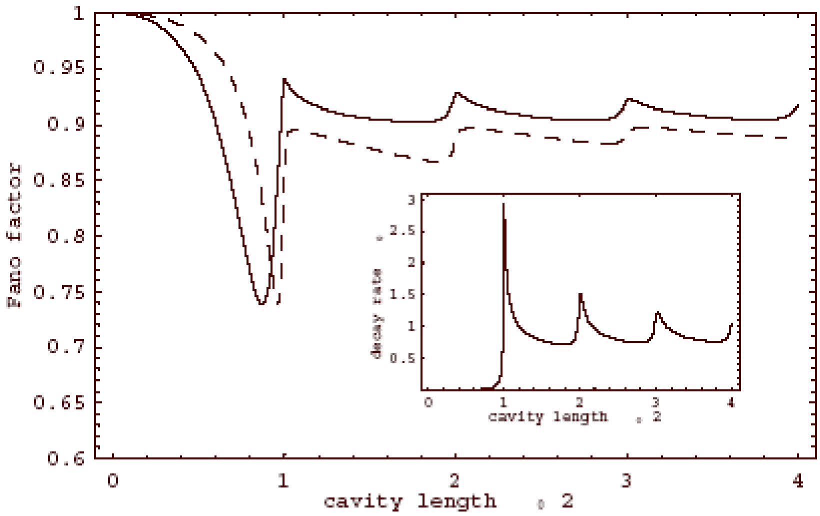

Fig.2

Since the current noise depends sensitively on the decay properties of a QR exciton, its emission rate inside a planar microcavity is numerically displayed in the inset of Fig. 2. As the cavity length is shorter than one half the wavelength of the emitted photon, the decay rate is inhibited because of the cut-off frequency of the cavity. One also notes that, at each resonant mode, there exists singular behavior, which is similar to that of a one- dimensional quantum wire in a microcavity. This is because the ring geometry preserves the angular momentum of the exciton, rendering the formation of exciton-polariton in the direction of circumference. This kind of behavior can also be found in the calculations of Fano factor as demonstrated by the solid line in Fig. 2. Comparing to the zero-frequency noise of the QD excitons (dashed line), the Fano factor of the QR excitons shows the "cusp" feature at each resonant mode.

Another interesting point is that below the lowest resonant mode, both the solid and dashed curves have a dip in the Fano factor. It is not seen from the radiative decay rate. The origin of this dip comes from that the zero-frequency noise is not a monotonic dependent function on the decay rate. If one plots Eq. (9) as a function of γ, it can be shown that the only minimum point appears at $\gamma = \Gamma_L\Gamma_R(\Gamma_L+\Gamma_R)/(\Gamma^2_L+\Gamma^2_R)$. This extra information about the tunneling rates of the two side barriers is extracted from the shot-noise spectrum, and is not available form dc transport measurement (steady state current).

II. Current noise of a quantum dot p-i-n junction incorporated inside a three-dimensional photonic crystal

We have also considered a QD *p-i-n* junction embedded in a three-dimensional photonic crystal (PC) as shown in Fig. 3. Similar to the case in above, the shot-noise can be obtained straightforwardly. However, one should note that the correlation function (in z-space) of the photon reservoir in a one-band PC is as follows:

$$C_\varepsilon(z) = \frac{-i\omega_0^2\beta^{3/2}}{\sqrt{\omega_c} + \sqrt{-iz - (\omega_0 - \omega_c)}}.$$

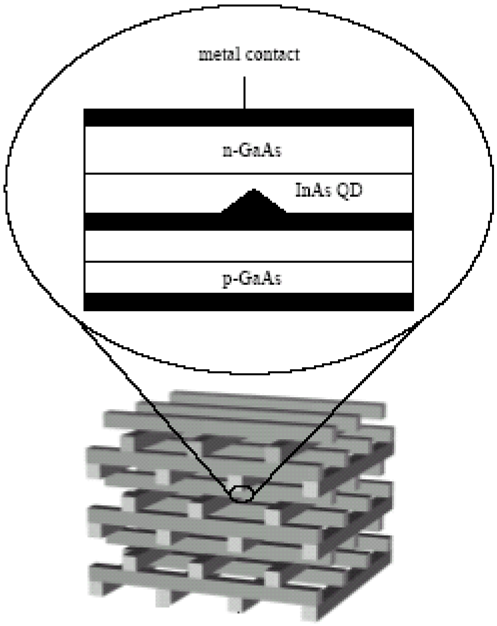

Fig.3 QD inside a p-i-n junction surrounded by a three-dimensional PC.

The corresponding current noise is shown in Fig. 4. As seen, the Fano factor shows the discontinuity as the exciton transition frequency is tuned across the photonic band gap (PBG) frequency (ω_c=101β). It also reflects that below the band edge frequency spontaneous (SE) of the QD exciton is inhibited. To observe this experimentally, the dc electric field (or magnetic field) can be applied to vary the band gap energy of the QD exciton. Another way to examine the PBG frequency is to measure the frequency-dependent noise as shown in the inset of Fig. 2, where the exciton band gap is set equal to 104β. As can be seen, discontinuities also appear as ω is equal to the *detuned* frequency between PBG and QD exciton.

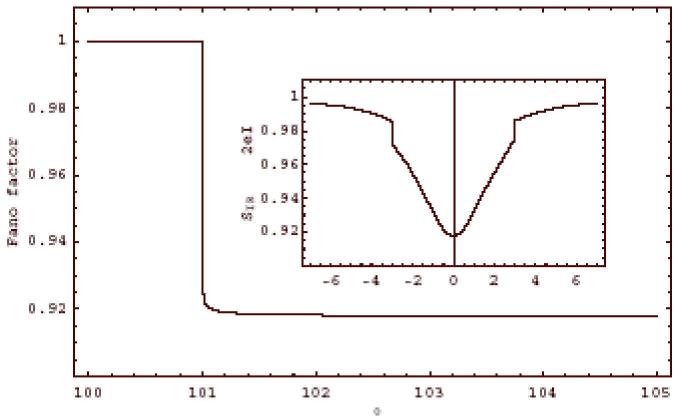

Fig. 4

We have also calculated the shot-noise spectrum of the QD *p-i-n* junction in a ***two-band*** PC. The photon correlation function is now written as

$$C_\varepsilon(z) = \frac{-i\omega_0^2\beta_1^{3/2}}{\sqrt{\omega_{c_1}} + \sqrt{-iz - (\omega_0 - \omega_{c_1})}} + \frac{i\omega_0^2\beta_2^{3/2}}{\sqrt{\omega_{c_2}} + \sqrt{iz + (\omega_0 - \omega_{c_2})}}.$$

One notes that there are two band edge frequencies, and the current noise should reveal this characteristic as shown in Fig. 5.

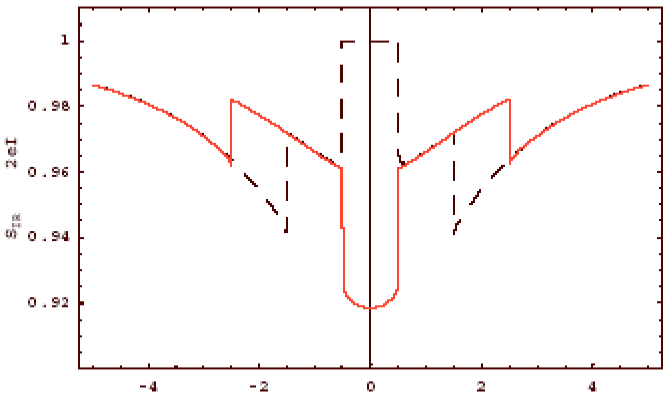

Fig. 5

The two band edge frequencies ω_{c1} andω_{c2} are set equal to 101β and 99β, respectively. There are three regimes for the choices of the exciton band gap: $\omega_0 > \omega_{c1}$, $\omega_0 < \omega_{c2}$, and $\omega_{c1} > \omega_0 > \omega_{c2}$. When ω_0 is tuned above the upper band edge ω_{c1} (or lower the lower band edge ω_{c2}), the QD exciton is allowed to decay, such that the shot noise spectrum (red curve) is downward in the range of $\omega < |\omega_0 - \omega_{c1}|$. On the other hand, however, if ω_0 is between the two band edges, SE is inhibited. As shown by the dashed curve, the behavior of the current noise in the central region is upward, and the value is equal to unity. Similar to the one-band PC, the curves of the shot noise spectrum reveal two discontinuities, demonstrating the possibility to extract information from a PC by the current noise.

A few remarks about the applications of the QDs inside a PC should be mentioned here. As known, controlling the propagation of light (waveguide) is one of the optoelectronic applications of PCs. If two QD *p-i-n* junctions can be incorporated inside a PC (and on the way of light propagation), the cavity-like effect can be used to create the entangled state between two QD excitons with remote separation. The advantages are that the decoherence of the entangled state can be suppressed because of the feature of the PBG, and observation of the enhanced shot noise could be an identification of the entangled state. Furthermore, if the entangled state is created between two dots, say dot-1 and 2, teleportation may be accomplished by the inclusion of the third dot with unknown exciton state.

4. 成果自評

We have successfully worked out the shot-noise spectrum of a QR in a planar microcavity or QD in a photonic crystal. As expected the current noise indeed reflect the characteristic of the *restricted* photons. This is remarkable since the *p-i-n* junction can in principle be used as a detector of photon noise. Moreover, we have also extended its applications in generating entangled states and achieving quantum teleportation. These findings are very interesting, and have attracted attention, e.g. ***our work was invited to become a chapter in the forthcoming book, "Quantum Dots: research development"***. We believe it certainly has important impact on the field of quantum information science. The followings are the publications supported by the project.

1. *Orientations of two coupled molecules***,** Y. Y. Liao, **Y. N. Chen**, and D. S. Chuu, Chem. Phys. Lett. **398,** 418 (2004).
2. *Effect of cavity and superradiance on the electrical transport through quantum dots*, **Y. N. Chen**, D. S. Chuu, and T. Brandes, Invited chapter in "Quantum Dots: research development", Nova Science Publishers (2005).
3. *Teleportation of charge qubits via superradiance*, **Y. N. Chen**, C. M. Li, D. S. Chuu, and T. Brandes, submitted to Phys. Rev. Lett. (2005).
4. *Current noise of quantum ring excitons incorporated inside a p-i-n junction*, **Y. N. Chen** and D. S. Chuu, submitted to Appl. Phys. Lett. (2005).
5. *Current noise of a quantum dot p-i-n junction incorporated inside a three-dimensional photonic crystal*, **Y. N. Chen**, D. S. Chuu, and T. Brandes, submitted to Phys. Rev. Lett. (2005).

5. 出席國際會議

預定出席 2005 年 5 月 22~26 日在維也納舉行的 Quantum Physics of Nature conference (QUPON). 我們的論文"Teleportation of charge qubits via superradiance"已被此會議接受發表，以下是接受發表的通知信函：

QUPON/QIPC 2005 Local Organizing Committee

Experimentalphysik, Universität Wien

Boltzmanngasse 5, 1090 Wien,

qupon@univie.ac.at, Tel: +43 1 4277 51201 (Claudia Hoffmann), Fax: + 43 1 4277 9512

Vienna, Saturday, 29 January 2005

Dear Dr. Chen,

we thank you very much for your submission of a contributed paper to the international conference QUPON 2005 (Quantum Physics of Nature) together with the EU Workshop QIPC 2005 (Quantum Information Processing and Communication).

We had by far more proposed talks, posters and interesting subjects than we could possibly host in a single week but we are glad to confirm, that

Your contribution was selected to be presented as a POSTER.

We would like to ask all accepted and confirmed participants of QUPON 2005 and QIPC 2005 to fill in the following form sheet as appropriate and to fax it to us at your earliest convenience.

Please update your contribution title and abstract online at http://www.quantum.at/QUPON/regupdate.php?RegNum=62&LastName=Chen, so that it can be included in the book of abstracts. Please keep to a space limit of 2000 characters. LaTex formatting, Word-Formatting or plain text are acceptable.

We are sorry to say that we cannot provide any financial support for contributed talks or posters nor can we waive fees – unless already otherwise confirmed by the organizers in very few selected cases. For QIPC members the EU officers have however agreed that participation in QUPON/QIPC can be reimbursed by your respective EU project funds, according to the usual rules for QIPC projects.

Please make sure that you don't miss the 'early payment' deadline, which is March 1st 2005.

We suggest that you reserve your accommodation as early as possible via the travel agent ALDA http://www.alda.at/exec/en/index.html. Vienna will be crowded in May both because of its unique flair in spring and for the several (Vienna Marathon, "life ball", various congresses etc.).

Ms. Ildiko Hotzi (i.hotzi@alda.at) is your contact partner with ALDA. She is informed about your participation, but she may still ask for your conference registration number. She will offer you a selection of hotels and accommodations. The conference organizers are not directly involved in the handling of hotel reservations. All accommodation charges or tourist arrangements organized via ALDA are to be paid by the participants directly to ALDA.

We are looking forward to fruitful discussions in Vienna

Gregor Weihs & Markus Arndt
(For the local organizing committee)