第31卷 第3期 发 光 学 报 Vol. 31 No. 3
2010年6月 CHINESE JOURNAL OF LUMINESCENCE Jun., 2010

Article ID: 1000-7032(2010)03-0341-07

The Effect of Structure and Magnetic Field on Resonant Tunneling Time in Triple-barrier Structures

JIA Guo-zhi[1], YAO Jiang-hong[2*], HE Jin-mi[2], YU Pei[2]

(1. *Tianjin Institute of Urban Construction*, *Tianjin* 300384, *China*;
2. *The Key Laboratory of Advanced Technique and Fabrication for Weak-Light Nonlinear Photonics Materials*, *Ministry of Education*, *TEDA Applied Physics School*, *Nankai University*, *Tianjin* 300475, *China*)

Abstract: To understand the dependence of the quasi-bound level energies E_z and the tunneling lifetime on the magnetic fields B, resonant tunneling in the triple-barrier structure was investigated by using the transfer matrix method. Transmission probability characteristics and the tunneling lifetime in the triple-barrier structure are investigated, respectively. The results showed that the first quasi-bound energy levels E_{1z} increase, while the second quasi-bound energy levels E_{2z} decrease with the increasing of the middle barrier thickness L. The lifetime τ of E_{1z} and E_{2z} is shortened with increasing of B and Landau quantum number n, and the effect of L on τ is weak for $B = 15$ and $n = 15$.

Key words: resonant tunneling; triple-barrier structure; transfer matrix theory

CLC number: O471.1 **PACS**: 73.20. –r; 73.40. Gk **PACC**: 7320D; 7335C **Document code**: A

1 Introduction

The resonant tunneling transmission properties in semiconductor multi-barrier structures have been extensively investigated for increasing interest in quantum physics mechanism and the potential application of high-speed and high-frequency devices[1,2] since the pioneering work of Tsu and Esaki[3]. The tunneling lifetime plays a decisive role in these devices to implement the perfect performance. Various theoretical methods have been developed to calculate the tunneling lifetime. Tsuchiya *et al* investigated a tunneling escape rate of electrons from a single quantum well through the thin barriers, and firstly predicted that the lifetime can be obtained from the energy width of the resonance transmission[4]. After that, Arsenault *et al*[5], Zou *et al*[6] and Peng *et al*[7] studied the resonant-tunneling lifetime of the double-barrier structure, respectively. Xu *et al*[8] had given out a simple analytical expression for the lifetime in an one-dimensional symmetrical double-barrier structure by solving the time-independent Schrödinger equation and using the energy uncertainty condition. Fisher *et al*[9] and Guo *et al*[10] investigated that the resonant tunneling energy level and width of a quasi-bound state in a double-barrier structure in an external electric field, respectively. Gong *et al*[11] studied the tunneling time of electrons through a parabolic quantum well structure theoretically, and found that the resonant tunneling lifetime through the parabolic quantum well is longer than that through the rectangular one in some cases. In the above methods, the tunneling lifetime was determined by measuring the full width at half maximum (FWHM) of the transmission coefficients, and then calculated by the energy uncertainty condition, which is a very simple and efficient method.

Recently, there has been increased interest in

Received date: 2009-11-09; **Revised date**: 2009-12-13
Foundation item: Supported by the Natural Science Foundation of Tianjin (09JCYBJC04100, 08JCYBJC14800); Science and Technology Plan Projects of the Ministry of Construction of China (2008-K7-10); Chinese National Key Basic Research Special Fund (2010CB933801)
Biography: JIA Guo-zhi, born in 1978, male, Shanxi Province. His work focuses on low dimension semiconductor physics.
E-mail: dip-coating@163.com
*: Corresponding Author; E-mail: yaojh@nankai.edu.cn

studying the effect of an external magnetic field on the resonant energy levels and the tunneling lifetimes of quasi-bound energy level in the low dimensional semiconductor structures due to the demand to understand the physics during the electron transport process and to develop the excellent performance device[12,13]. Obviously, some important parameters, including quasi-bound energy levels and tunneling lifetime can be influenced by an external magnetic field[12]. Although Wang *et al* presented an investigation about electrons tunneling through a double-barrier structure under an external magnetic field, it is necessary to further understand the effect of an external magnetic field on the tunneling lifetime in the triple-barrier structure.

Very recently, quantum rings (QRs) have attracted a lot of attention due to the occurrence of the Aharonov-Bohm effect and highly uniform in size distribution. In our previous study, high density and uniform QRs can be obtained by the postgrowth technique[13]. Li *et al* investigated the transmission probability of a single electron transmission through a QR device based on the single-band effective mass approximation method. It is that the electron tunneling resonance peaks split when the electron transmits through a double QR[14]. The similar transmission properties can be observed in the triple-barrier structure, which excited us to investigate the transmission properties in the triple-barrier structure again. Furthermore, a complete revealing of this physics process of electron tunneling through the triple-barrier structure can be very important to the designing of high performance quantum computing and high-speed semiconductor device. In addition, it should be pointed out that the coupling between the energy levels in the different confining potentials and the different energy levels in the same confining potential plays crucial role in transmission properties of electron.

In this paper, we discuss the dependence of the quasi-bound energy levels and lifetime in triple-barrier structure on the structure and longitudinal magnetic fields This paper is organized as follows. In section 2, we introduce the structure parameters of the triple-barrier structure and transfer matrix method. In section 3, transmission probability characteristics in the triple-barrier structure are investigated; then numerical calculations are carried out to reveal the elaborate dependence of the quasi-bound energy level lifetime on structure parameters using the energy uncertainty condition. At the same time, the effect of the longitudinal magnetic fields and Landau quantum number on the lifetime of quasi-bound energy level is analyzed. In section 4, the results of this work are summarized.

2 Theory

The schematic energy diagram of the triple-barrier structure under investigation is shown in Fig. 1. A single electron propagating with energy E from left to right is simulated by the transfer matrix method and takes effective mass approximation into account. Here, L_1, L_2, and L_3 are the thickness of the barriers, b_1, and b_2 the width of wells, U_1, U_2, and U_3 are the barrier heights of the triple-barrier structure. It was assumed for all simulation that the structures consist of $Al_xGa_{(1-x)}As$ barriers and GaAs wells. The effective electron mass in $Al_xGa_{(1-x)}As$ is expressed as $(0.067 + 0.083\ )m_0 (0 \leqslant x \leqslant 1)$, m_0 is electron mass in vacuum. The effective electron mass in GaAs well is $0.067m_0$.

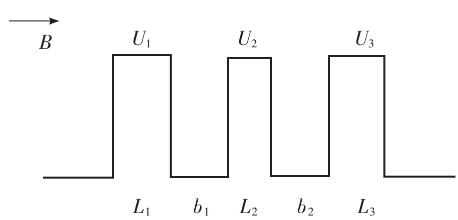

Fig. 1 Potential energy diagram of the triple-barrier structure, and the definition of the symbols. L_1, L_2, and L_3 are the barrier thickness, b_1 and b_2 are the well width, and U_1, U_2, and U_3 are the barrier heights. B is the magnetic field intensity.

The theoretical model is mainly described when a longitudinal magnetic field was considered. An external homogeneous longitudinal magnetic field B is applied perpendicular to interfaces along this growth axis. The symmetric gauge for the vector potential can be described as

$$A = \frac{1}{2} B \times r, \quad (1)$$

The Hamiltonian of the electron in the effective-mass nonparabolic conduction-band model can be given as follows [15] :

$$\hat{H} = \left(\frac{1}{2} + \hat{n}\right)\hbar\omega(z) + \frac{1}{2}\hat{p}_z \frac{1}{m(z)}\hat{p}_z + U(z), \quad (2)$$

where $\omega(z) = eB/m(z)$ is the position-dependent cyclotron-frequency of the electron, $U(z)$ is the potential function, $\hbar$ is the reduced Planck constant, $\hat{n}$ is the occupation number operator of the harmonic oscillator. As the effective mass is considered, the Landau levels E_n are no longer conservative as a result of $[\hat{n}, \hat{H}] = 0$, which prevents the separation of the total energy into transverse and longitudinal components.

Taking the conservation of n into account, so we can separate the 3D wave function of the electron as:

$$\Psi(r) = \Theta_n(x,y)\Phi(z), \quad (3)$$

where $\Theta_n(x,y)$ is the harmonic oscillator eigenfunction with the Landau-level indices $n = 0, 1, 2, 3 \cdots$. Substituting the wave function (3) into the eigenequation, then the longitudinal wave $\Phi(z)$ satisfies the following modified one-dimensional Schrödinger equation

$$-\frac{\hbar}{2}\frac{\mathrm{d}}{\mathrm{d}z}\frac{1}{m(z)}\frac{\mathrm{d}}{\mathrm{d}z}\Phi(z) + U_{\mathrm{eff}}(z)\Phi(z) = E_z^{\mathrm{w}}\Phi(z), \quad (4)$$

where $E_z^{\mathrm{w}} = E - \left(\frac{1}{2} + n\right)\hbar\omega_{\mathrm{w}}$ is the longitudinal energy of the electron in the well regions, and $U_{\mathrm{eff}}(z)$ is the effective potential function. Thus, the effective barrier height is quantized by magnetic field due to magneto-coupling effect, and can be given by

$$U(n,B) = U_0 - (1-\gamma)\frac{\hbar^2 k_{\mathrm{n}}^2(B)}{2m_{\mathrm{w}}}, \quad (5)$$

where $\gamma = m_{\mathrm{w}}/m_{\mathrm{b}}$, $k_{\mathrm{n}}^2(B) = (2eB/\hbar)\left(\frac{1}{2} + n\right)$, and m_{w}, m_{b} the effective mass in quantum well and barrier, respectively.

The lifetime of quasi-bound energy levels was calculated by the energy uncertainty condition [4~9] :

$$\tau = \frac{\hbar}{2\Delta E}, \quad (6)$$

ΔE is the half-width of the resonant peak at half-maximum of the resonant peak around the resonance energy E_{m}. The half-width ΔE is obtained from the graph of the transmission coefficient versus incident energy. The transmission coefficient through the triple-barrier structure can be determined by transfer matrix method. The detailed method can be found in many articles with the relation to resonant tunneling.

3 Results and Discussion

Fig. 2 shows the variation of the transmission coefficient versus the incident longitudinal energy E_z for different middle barrier thickness L_2 at the magnetic field intensity $B = 10$ Tesla and Landau quantum number $n = 10$. It can be seen that the split of resonance peaks strongly depends on L_2. It's well known that the split resulted from the coupling between the localized states, and the separation reflects the degree of the coupling between quasi-bound energy levels, and strongly depends on L_2. As L_2 increases, the separation between the first quasi-bound energy level and the second one decrease due to the coupling becoming weaker, which is similar with the results without taking magnetic field and Landau quantum number into account [16]. More important,

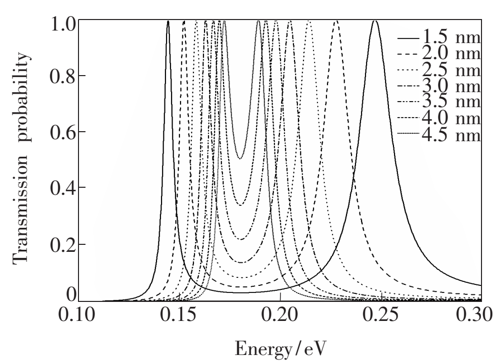

Fig. 2　Tunneling probability as a function of longitudinal electron energy E_z at the magnetic field intensity B = 10 Tesla and Landau quantum number $n = 10$ for the middle barrier thickness L_2 = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 nm in a triple-barrier structure. The structure parameters are set to be $b_1 = b_2 = 2.0$ nm, $L_1 = L_3 = 3.0$ nm, $U_1 = U_2 = 0.3$ eV, $m_b^* = 0.1002 m_e$, and $m_0^* = 0.067 m_e$.

it is clear that the energy width of transmission probability peak has been greatly changed with increasing of L_2.

In order to further analyze the effect of L_2, the magnetic field intensity B and Landau quantum number n on the quasi-bound energy levels, the dependence of the quasi-bound energy levels on L_2 in triple-barrier structure with different B and n is shown in Fig. 3. As L_2 increases, E_{1z} shifts to the higher energy regions quickly, while E_{2z} to the lower energy regions. The resonant peaks shift to the low energy region under the influence of magnetic field, which can be ascribed to the decreasing of the effective barrier height, while the changing of E_{2z}, originating from the coupling between energy levels in two separation wells, and can be weakened due to the increase of L_2. As well known, the quasi-bound states in the well of the multi-barrier structure are formed by the multiple coherent reflections of the electronic wave function at the boundaries of the barrier scattering potential. The Landau quantum number and the magnetic field intensity influence on the height of the barrier potential, which can further influence on the coupling between the quasi-bound energy levels. That is to say, the resonant energy levels and tunneling time not only are related to the Landau quantum number and the magnetic field intensity, but also to the coupling between energy levels.

It is very different from the result of the triple-barrier structure under a bias voltage. When a bias

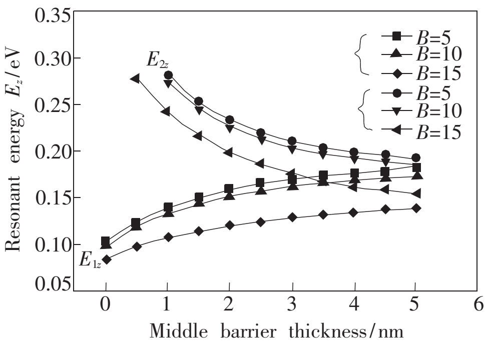

Fig. 3 Variation of the first and the second resonant quasi-bound energy level as a function of the middle barrier thickness at the different magnetic field intensity B and Landau quantum number n. The structure parameters correspond to that in Fig. 2.

voltage is applied to a triple-barrier structure, resulting in the barrier tilted, the transmission probability can be reduced due to the breakdown of the symmetry of the corresponding structure[10]. The magnetic field can't make the barrier tilt, thus the transmission probability isn't influenced, only make the resonant peak shift. In addition, the changing of E_{1z} and E_{2z} are fast followed by slow with the increase of L_2, and as the middle barrier was thinned to a certain degree, the second quasi-bound state vanishes, which can be ascribed to the coupling between wave functions in the two separation wells. The coupling of the wave functions increases with the decrease of the middle barrier thickness due to the strong dependence of energy shift on L_2, the changing of energy levels is fast. At the same time, it is shown that the E_{2z} changes much faster than E_{1z} with the increasing of L_2, which implies the second quasi-bound states are sensitive to the middle barrier thickness caused by the coupling between energy levels. Furthermore, it also shows that when $L_2 = 5$ nm, the first energy levels will intersect with the second one, and the convergent point markedly shift to the low energy region with the increasing of B and n, which further indicated that B and n can importantly influence on the effective barrier height and the coupling between the different energy levels.

Fig. 4 presents the tunneling lifetime of the first and the second quasi-bound states as a function of L_2 under the different magnetic field intensity B and Landau quantum number n. It is clearly seen that the tunneling lifetime τ_1 of the first quasi-bound energy level decreases as the increasing of L_2 in the fixed magnetic field intensity B and Landau quantum number n, while having an inversion effect on τ_2. It can also be noticed that the further increase of B and n results in further τ_1 shorten. Much higher B and n, for example, $B = 15$ and $n = 15$, lead to drastically decrease of τ_1. It is worth notice that for $B = 15$ and $n = 15$, effect of L_2 on τ_1 is very small, only 0.02 ps variation. As for the tunneling lifetime of the second quasi-bound energy level, the same behavior of τ_2 for three different B and n values can be found. The tendency of the tunneling lifetime changing with the increasing of L_2 for different B and n originates from the changing of the effective barrier height. It is widely believed that the effective barrier height and the coupling between the quasi-bound energy levels contribute to variation of the tunneling lifetime. It is very difficult to exactly know which contributes more and which less. At the same time, we observed that the electrons in the second quasibound energy levels could have shorter tunneling lifetime than that in the first quasi-bound energy levels do. The thinner the middle barrier is, the stronger the coupling strength between quasi-bound energy levels, the larger the minimum separation, resulting in a faster tunneling time through the barrier.

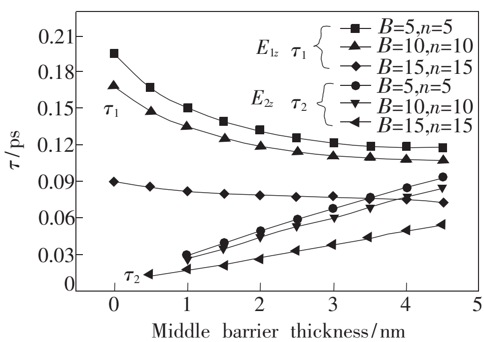

Fig. 4　Variation of tunneling time of the first and the second resonant quasi-bound energy level as a function of the middle barrier thickness at the different magnetic field intensity B and Landau quantum number n. The structure parameters correspond to that in Fig. 2.

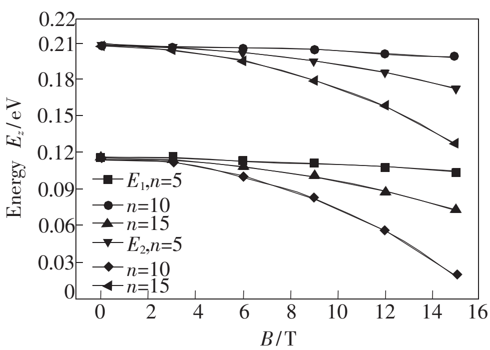

Fig. 5　The dependence of the resonant tunneling energy levels on the magnetic field intensity B at the Landau quantum number n = 5, 10, 15. E_1 and E_2 correspond to the first and the second quasi-bound energy level, respectively. The structure parameters are set to be $b_1 = b_2 = 2.0$ nm, $L_1 = L_2 = L_3 = 3.0$ nm, $U_1 = U_2 = 0.3$ eV, $m_b^* = 0.100\ 2m_e$, and $m_0^* = 0.067m_e$.

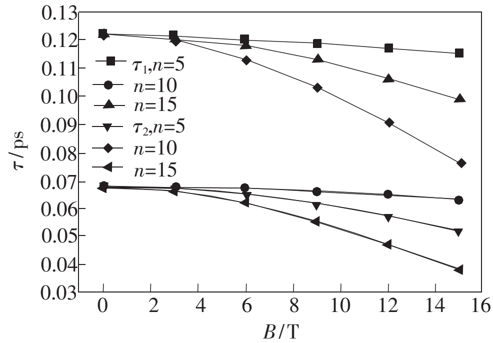

Fig. 6　The dependence of the resonant tunneling time on the Landau quantum number n at the magnetic field intensity B = 5, 10, 15. τ_1 correspond to the first quasi-bound energy level, and τ_2 to the second one. The structure parameters correspond to the Fig. 5.

Fig. 5 and Fig. 6 show the dependence of the resonant energy levels and the tunneling time on the magnetic field intensity B at the Landau quantum number n = 5, 10, and 15, respectively. In Fig. 5, with the B increasing, resonant energy levels E_{1z} and E_{1z} shifted to the lower energy region. The larger n is, the rapider reduction of the resonant energy is. That is due to lowering the effective potential barrier when the magneto-coupling effect is taken into account. In Fig. 6, we can see that the magneto-coupling effect results in the tunneling time shortening rapidly.

4　Conclusion

In this paper, we have investigated the influence of the structure parameters and magneto coupling on the resonant energy level and tunneling lifetime in the triple-barrier structure by using the effective mass approximation and transfer matrix theory in detail. The effect of the middle barrier thickness on the quasi-bound energy levels and the tunneling lifetime has been simulated and analyzed. The result shows that the energy levels and lifetime are insensitive to the thickness of the middle barrier for the strong magnetic field and high Landau quantum number. In generally, the tunneling lifetime can be shortened with increasing of the B and n due to the magneto-coupling effect.

References:

[1] Regan B C, Aloni S, Jensen K, *et al.* Surface-tension-driven nanoelectromechanical relaxation oscillator [J]. *Appl. Phys. Lett.*, 2005, **86**(12):123119-1-3.

[2] Mi Z, Bhattacharya P, Fathpour S. High-speed 1.3 μm tunnel injection quantum-dot lasers [J]. *Appl. Phys. Lett.*, 2005, **86**(15):153109-1-3.

[3] Tsu R, Esaki L. Tunneling in a finite superlattice [J]. *Appl. Phys. Lett.*, 1973, **22**:562-565.

[4] Tsuchiya M, Matsusue T, Sakaki H. Tunneling escape rate of electrons from quantum well in double-barrier heterostructures [J]. *Phys. Rev. Lett.*, 1987, **59**(20):2356-2359.

[5] Arsenault C J, Meunier M. Resonant-tunneling lifetime comparison between double-barrier and δ-doped barrier structures [J]. *Phys. Rev.* B, 1989, **39**(12):8739-8742.

[6] Zou Nanzhi, Rammer J, Chao K A. Tunneling escape of electrons from a double-barrier structure [J]. *Phys. Rev.* B, 1992, **46**(24):15912-15921.

[7] Peng Jianping, Mu Yaoming, Shen Xuechu. Resonant level lifetime in the double-barrier structure for both quasi-bound and extended states [J]. *J. Appl. Phys.*, 1993, **73**(2):989-991.

[8] Huaizhe X, Meifang Z, Boyuan H. Analytical expressions for resonant-tunneling lifetime in symmetrical double-barrier structures [J]. *Phys. Lett.* A, 1996, **223**(4):227-231.

[9] Fisher D J, Zhang C. Electron tunneling lifetime of a quasibound state in a double-barrier resonant tunneling structure [J]. *J. Appl. Phys.*, 1994, **76**(1):606-608.

[10] Guo Yong, Gu Binglin, Yu Jingzhi, *et al.* Resonant tunneling in step-barrier structures under an applied electric field [J]. *J. Appl. Phys.*, 1998, **84**(2):918-924.

[11] Gong J, Liang X X, Ban S L. Tunneling time of electronic wave packet through a parabolic quantum well with double barrier [J]. *Phys. Status Solidi* (b), 2007, **244**(6):2064-2071.

[12] Wang Hongmei, Zhang Yafei, Xu Huaizhe. The effect of transverse wave vector and magnetic fields on resonant tunneling times in double-barrier structures [J]. *J. Appl. Phys.*, 2007, **101**(2):023712-1-5.

[13] Jia Guozhi, Yao Jianghong, Shu Yongchun, *et al.* Quantum rings formed in InAs QDs annealing process [J]. *Appl. Surf. Sci.*, 2009, **255**(8):4452-4455.

[14] Li Chunlei, Yang Fuhua, Feng Songlin, *et al.* Transmission properties of electron in quantum rings [J]. *J. Appl. Phys.*, 2008, **103**(6):063723-1-5.

[15] Wang Xuehua, Gu Benyuan, Yang Guozhen. Coupling between normal and lateral degrees off reedom of an electron in quantum wells and superlattices at zero and finite magnetic fields [J]. *Phys. Rev.* B, 1997, **56**(15):9224-9227.

[16] Xu D X, Shen G D, Willander M, *et al.* The properties of resonant transmission in triple-barrier/double-quantum-well heterostructures [J]. *J. Appl. Phys.*, 1992, **71**(8):3859-3864.

结构和磁场对三势垒结构中共振隧穿时间的影响

贾国治[1], 姚江宏[2*], 何进密[2], 于 沛[2]

(1. 天津城市建设学院, 天津 300384;

2. 弱光非线性光子学教育部重点实验室 南开大学 泰达应用物理学院, 天津 300475)

摘要: 为了理解在三势垒结构中准束缚能级 E_z 和隧穿寿命对磁场的依赖性,采用传输矩阵的方法研究了在三势垒结构中的共振隧穿过程。分别研究了在三势垒结构中的透射几率特征和隧穿寿命。结果表明:随着中间势垒厚度 L 的增加,第一准束缚能级 E_{1z} 增加,而第二准束缚能级 E_{2z} 却减小。随着磁场强度 B 和朗道量

子数 n 的增加,与第一和第二准束缚能级(E_{1z},E_{2z})对应的寿命 τ 缩短。对于 $B=15$ 和 $n=15$ 的情况,L 对 τ 的影响很小。

关　键　词: 共振隧穿; 三势垒结构; 传输矩阵理论

中图分类号: O471.1　**PACS:** 73.20.-r; 73.40.Gk　**PACC:** 7320D; 7335C　**文献标识码:** A

文章编号: 1000-7032(2010)03-0341-07

收稿日期: 2009-11-09; **修订日期:** 2009-12-13

基金项目: 天津自然科学基金面上 (09JCYBJC04100, 08JCYBJC14800); 建设部科技计划研究项目(2008-K7-10); 国家重大基础研究计划(2010CB933801)资助项目

作者简介: 贾国治(1978 –), 男, 山西人, 主要从事发光材料方面的研究。
E-mail: dip-coating@163.com
*: 通讯联系人; E-mail: yaojh@nankai.edu.cn