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评 述

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量子点与光子晶体微腔的耦合

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摘要 近20年来, 量子点与光子晶体微腔的耦合体系受到了国内外的广泛关注, 并取得了迅速的发展. 它提供了一个有效的光与物质相互作用的量子界面, 在光学器件的优化以及量子信息处理等方面都有广泛的应用前景; 同时, 它具有高集成度, 通过与波导集成可实现片上集成的光学芯片. 本文主要介绍了自组织生长量子点与光子晶体微腔及其耦合体系的基本原理和实验进展, 并展望了该耦合体系的发展趋势与应用前景.

关键词 量子点, 光子晶体微腔, 腔量子电动力学, 强耦合, 弱耦合

量子信息科学在近几十年来取得了快速的发展, 但距离它的实际应用仍面临着巨大的挑战, 比如实现规模化的量子网络. 为此, 可规模化的量子比特是不可或缺的, 它是量子信息的载体. 目前国内外已研究出多种可用作量子比特的物理体系[1~3], 包括光子[4]、原子[5,6]、固态量子体系[7~9]、超导体系[10]等. 其中光子可作为飞行量子比特, 用来传输信息, 而固态量子体系由于易于集成的特性, 可作为量子网络中的固定节点, 通过飞行量子比特连接起来[11]. 在这个过程中, 一个有效的光与物质相互作用的量子界面是必需的, 而腔量子电动力学为构建这一有效的量子界面提供了一个很好的方法[8].

腔量子电动力学研究的是光与物质在量子水平的相互作用, 即光子与量子能级之间的相互作用. 由于量子能级的辐射特性不是固有的, 它可以通过控制量子能级的光学环境来操控[12]. 因此, 利用与光学微腔的耦合, 光与量子能级之间的相互作用可以被大大提高. 根据它们之间的耦合强度与衰减速率之间的大小关系, 该耦合体系可以分为弱耦合和强耦合体系[8,13,14]. 在弱耦合体系下, 量子能级的自发辐射速率会得到增强[14]; 而在强耦合体系下, 能量会在量子能级与光子之间发生振荡, 形成新的量子态[13]. 为了研究腔量子电动力学, 我们一方面需要具有良好量子特性的量子体系[9], 另一方面需要具有高品质因子、低模式体积的光学微腔[14].

本文主要关注的是自组织量子点与光子晶体微腔的耦合体系. 自组织量子点具有优良的光学特性, 在单光子源[15~22]、纠缠光子源[23~34]、量子比特[35~42]、激光[43~45]等方面都有突出的优势; 而光子晶体微腔具有高品质因子、低模式体积, 能够提供很强的光束缚能力, 可以显著地增强光与物质的相互作用[14,46~49]. 同时, 光子晶体微腔易于与量子点集成, 利用它们的弱耦合体系, 可以优化光学器件的性能; 而利用它们的强耦合体系, 可以发展新型光学器件, 研究单光子量级的非线性光学等. 它们的耦合体系可以作为量子网络的节点, 并通过波导连接起来, 为实现片上集成的量子网络提供了一个很好的平台[11,50]. 本文主要介绍了自组织生长量子点与光子晶体微腔及其耦合体系的基本原理,

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并介绍了目前的实验进展和该体系的应用前景.

1 自组织生长量子点

半导体量子点是一种三维受限的纳米结构，它的尺寸一般在纳米量级. 虽然它包含成千上万个原子, 但是由于受到纳米尺度的三维量子限制，它具有类似于原子的分立能级, 因此被称为“人工原子”. 受益于成熟的半导体生长、加工工艺，目前已经发展出多种半导体量子点生长方法，例如Stranski-Krastanow方法[51,52]、液滴外延方法[53]等. 其中Stranski-Krastanow方法是最为常见的一种，它通过分子束外延在GaAs衬底上生长一层很薄的InAs或InGaAs湿层，由于InAs或InGaAs与GaAs材料之间的晶格失配(7%)，InAs或InGaAs湿层内会存在应力，应力通过形成岛状结构得到释放[54], 这些岛状结构即为量子点, 如图1(a)所示[55]. 为了形成三维受限同时避免氧化，之后会在量子点上继续生长一层GaAs材料. 由于在该过程中，量子点是通过生长过程中沉积材料的应力释放形成的岛状结构，是沉积材料自组装的过程，因此被称为自组织生长量子点.

通常，自组织生长量子点的高度在1~10 nm，水平方向的尺寸在10~70 nm. 这种纳米尺度的束缚使量子点在导带和价带形成了分立的能级，如图1(b)所示. 通过激发, 量子点中会产生激子, 即电子-空穴对. 通过控制生长过程可以控制量子点的尺寸、应力分布以及掺杂等[56~60], 从而实现激子发光波长的有效调节, 其波长范围一般在850~1550 nm. 利用激子态的光学跃迁，单个量子点可以产生单光子. 相比其他量子点, 自组织生长量子点具有优良的光学性质，在单光子源的各个性能上均有突出的表现，包括高纯度(>99%)、高不可区分度(99%)以及高亮度[20,21]. 而且，自组织生长量子点中的基态和激子态可以构成量子比特中的两个逻辑态, 利用激光光谱可以实现对量子比特的操控[61]. 但是, 由于自发辐射的影响, 激子态的相干时间太短, 限制了它的实际应用[38]. 除了光学跃迁允许的亮激子态外, 量子点中还存在光学跃迁禁止的暗激子态[62]. 通过施加水平磁场(Voigt构型)，可以在光致发光谱和光电流谱中观测到暗激子态[63,64]. 相比亮激子态, 暗激子态具有很长的相干时间，在量子比特方面有广泛的应用前景[65,66].

除了单激子态外，量子点中还具有丰富的多激子态，例如双激子态和带电激子态. 双激子态由两对电子-空穴组成，通过双激子态到单激子态再到基态的跃迁，会产生级联光子. 根据不同的衰减路径，可以得到不同偏振的级联光子, 因此可用作纠缠光子源[23~34]. 而带电激子态相比于单激子态多了一个电子或空穴，它可以通过在生长过程中掺杂或通过施加电场等方法产生[67~70]. 利用带电激子态, 可以通过光场、电场、磁场等实现对单个电子或空穴自旋的有效操控[38,71~78]，且量子点中电子或空穴的自旋态具有较长的相干时间，因此可作为量子比特的载体[38].

相比于其他量子体系[9,79]，例如原子、稀土离子、缺陷中心、二维材料、碳纳米管、胶体量子点等，自组织生长量子点具有优良的光学特性，在激光、单光子源、纠缠光子源、量子比特以及太阳能电池等方面都有广泛的应用前景. 而且，通过控制生长过程，施加

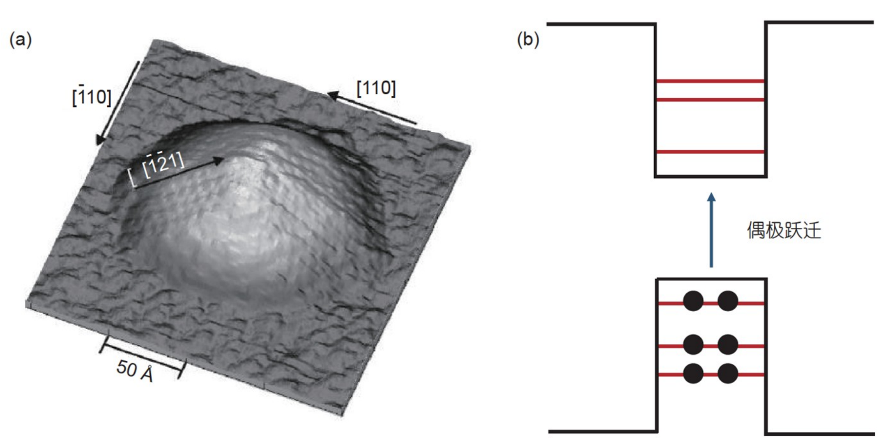

图 1 (网络版彩色)自组织生长量子点的表征. (a) 自组织生长量子点的扫描隧道显微镜图像[55]; (b) 自组织生长量子点的能级示意图
Figure 1 (Color online) Characterization of self-assembled quantum dots. (a) Scanning tunneling microscope image of self-assembled quantum dots[55]; (b) energy level of self-assembled quantum dots

磁场、电场、光场、应力场以及与光学结构耦合等方法, 自组织生长量子点的物理特性会得到有效调控.

2 光子晶体微腔

光子晶体是折射率周期性排布的结构. 在二维体系下, 光子晶体一般通过介质柱的周期性排布或者在介质平板上刻蚀空气孔实现[80]. 二维GaAs平板光子晶体通过在GaAs平板上刻蚀周期性的空气孔形成. 在这种结构中, 水平方向上光的传播受光学布拉格散射控制, 类比于晶体中电子的布拉格散射. 通过设计光子晶体的排布, 它会出现光学带隙, 即在这个范围内的光无法在光子晶体中传播. 因此, 通过引入点缺陷, 例如移去部分空气孔或调节局部空气孔的位置和大小, 就能实现束缚的光学模式, 即光学微腔模式. 这种光学模式在水平方向上受光学带隙束缚, 在竖直方向上受全反射束缚. 同样地, 在光子晶体结构中移去一排空气孔, 可以形成用于传输的波导模式. 图2展示了一种光子晶体微腔和光子晶体波导的扫描电子显微镜图像.

光子晶体微腔的形成机理决定了它具有非常灵活的设计性. 一方面, 可以灵活设计缺陷的类型, 得到不同类型的光子晶体微腔, 例如H0[81,82]、H1[83~85]、L3[48,86,87]、L4/3[88,89]、异质结型微腔[49,90~92]等. 其中, H0型微腔通过调节局部空气孔的位置和大小实现; H1、L3型微腔通过移去1或3个空气孔得到; L4/3型微腔是先移去3个空气孔, 然后再加上4个空气孔形成的; 异质结型微腔是通过调节光子晶体波导中不同区域的周期从而构成异质结得到的. 这些光学微腔具有不同的光学特性, 包括模式体积、品质因子、偏振、对称性以及场分布等, 因此可实现不同的功能. 另一方面, 还可以通过调节缺陷周围空气孔的位置和大小, 进一步优化光学微腔的性能, 例如品质因子. 2003年, Noda课题组[48]通过调节缺陷边缘空气孔的位置, 将L3型光子晶体微腔的品质因子优化到了10^4, 取得了突破性成就, 为之后光子晶体微腔的优化提供了思路. 之后, 国内外学者基于此思路提出了不同类型的光子晶体微腔, 并对其进行了优化[81,83,85,91]. 并且, 最近还提出了利用机器学习的方法对光学微腔的品质因子进行优化[81]. 目前, 光子晶体微腔的品质因子理论值最高可达10^9[91].

除了理论值的优化外, 制备过程的优化也是不可或缺的, 尤其对于有源的GaAs平板光子晶体. 它们存在较强的光吸收和较多的缺陷, 而且在制备过程中也会引入制备误差, 这些都会对制备结果产生影响, 导致制备的品质因子远小于理论值, 并且理论值越大, 差距越大. 为了优化实验值, 一方面, 需要优化制备过程, 减小制备误差; 另一方面, 可以通过表面钝化处理, 减少表面的吸收, 从而优化制备的品质因子[92]. 其中, 通过表面钝化处理, 制备的品质因子可以增加3倍左右, 最高可达10^6量级[92].

除了高品质因子外, 光子晶体微腔还具有较低的模式体积, 大部分均小于$(\lambda/n)^3$, 这大大增强了光与物质的相互作用, 提高了它们之间的耦合强度, 为实现强耦合体系打下了基础. 而且, 光子晶体微腔还具有高集成性, 能够实现多个微腔之间的耦合以及与波导的集成, 为实现片上集成的光学网络提供了一个很好的平台.

3 量子点与光子晶体微腔的耦合

量子点与光子晶体微腔的耦合可以根据它们的耦合强度g及该体系衰减速率之间的大小关系分为弱耦合体系和强耦合体系[8,13,14]. 其中, 在偶极近似下, 量子点与光子晶体微腔的耦合强度$g=\boldsymbol{\mu}\cdot\boldsymbol{E}/\hbar$, 其中$\boldsymbol{\mu}$为量子点的偶极矩, $\boldsymbol{E}$为量子点所在位置的电场强度. 当耦

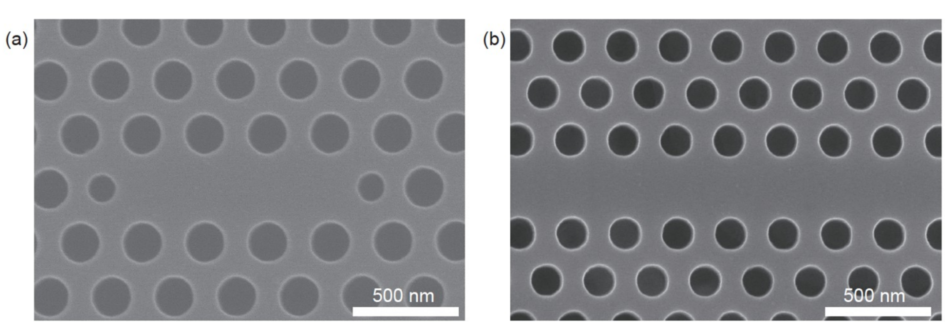

图 2 光子晶体结构的扫描电子显微镜图片. (a) L3型光子晶体微腔; (b) 光子晶体波导

Figure 2 Scanning electron microscope images of photonic crystal structures. (a) Photonic crystal L3 cavity; (b) photonic crystal waveguide

合强度小于衰减速率时, 该耦合体系为弱耦合. 在这种情况下, 由于局域态密度的增加, 量子点的自发辐射速率得到增强, 增强的倍数为Purcell因子, 即为Purcell效应, 如图3(a)所示. 当量子点位于场强最大的位置时, 可得到最大的Purcell因子, 为$F_\mathrm{p}=\frac{3Q(\lambda/n)^3}{4\pi^2V}$, 它与微腔的品质因子$Q$成正比, 与模式体积$V$成反比[14]. 通过提高品质因子、降低模式体积, 可以提高量子点的Purcell因子, 进一步加快量子点的自发辐射速率. 而当耦合强度大于衰减速率时, 该耦合体系会进入强耦合. 在这种情况下, 能量会在量子点与微腔中来回交换, 发生拉比振荡, 形成新的量子态, 即激子极化激元, 如图3(b)所示. 形成的激子极化激元会发生能量劈裂, 为拉比劈裂, 它的大小约等于$2g$. 由于耦合强度g与量子点的偶极矩和电场强度成正比, 因此, 为了提高耦合强度, 一方面可以利用具有大偶极矩的量子点, 另一方面可以优化量子点的位置, 使其位于场强最大的地方, 同时减小模式体积, 提高最大场强. 实验上, 强耦合现象通常通过频域上的拉比劈裂或者时域上的拉比振荡来表征[13,86,93,94].

在弱耦合体系下, 量子点的自发辐射速率会得到增强, 因此可以用来优化光学器件的性能. 例如, 量子点可作为量子光源, 通过与光子晶体微腔耦合, 可以降低单光子发射的时间抖动, 提高量子效率等, 因此可用作高效单光子源[95,96]和纠缠光子源[97]. 量子点可以与波导集成, 利用π脉冲激光共振激发可实现高效的、片上集成的按需单光子源[96]; 同时, 它们的弱耦合体系可以降低激光的阈值, 实现超低阈值甚至无阈值激光[44~47,98,99], 还可以实现单量子点的激射[100,101]. 而且, 量子点可以用作自旋比特, 通过与微腔弱耦合, 可以实现超快自旋比特操控, 例如超快自旋初始化、高效单光子探测等[37,38]. 除此之外, 微腔还可以增强非线性效应, 例如增强量子点与激光形成的Mollow triplet[102]以及拉曼跃迁[103]等.

在强耦合体系下, 能量会在量子点与微腔光子中来回交换, 这是一个可逆的过程. 因此, 利用强耦合体系可以实现量子信息在量子点与光子之间的相干交换, 从而可用来实现量子态的传送. 并且, 在强耦合状态下, 量子点与光子的状态是纠缠的, 也就意味着其中一种量子态可以用来控制另一种量子态, 因此可用来实现量子逻辑门、光开关等[37~41,104]. 此外, 可以通过多种方式实现对量子点和光子晶体微腔的调控, 例如电场、磁场、光场、应力场等[105~108]. 其中, 利用全光控制可以达到ps量级的操控速率[108], 为量子态的超快操控提供可能. 而且, 量子点与光子晶体微腔的耦合体系遵循Jaynes-Cummings量子模型, 它会产生非简谐的能级分布, 即拉比劈裂的大小跟参与耦合的光子数n有关, 因此单个光子的吸收会对之后的光子产生影响, 即产生了单光子的非线性效应, 且随着耦合强度的变大, 该影响变大[109]. 目前已证明的单光子非线性效应包含单光子阻塞以及光子诱导隧穿等, 这些可以用来实现单光子光开关[110]、非经典光的产生[111]以及光与光的强相互作用[112]等. 同时, 这种耦合体系也为研究量子的非线性光学提供了一个很好的平台.

图4(b)总结了量子点与光子晶体微腔强耦合的一些主要应用. 除此之外, 由于量子点中存在丰富的激子态, 因此它为研究腔量子电动力学提供了更加丰富、多样的平台. 例如, 许秀来课题组[113]通过激子态与双激子态同时与光子晶体微腔发生强耦合, 并且其耦合强度均为130 μeV, 首次证明了双光子拉比劈裂, 如图5所示. 该工作将腔与量子点的强耦合体系由单光子推向了双光子过程, 为多量子比特的操控提供了手段. 并且, 在量子点p壳层激子与光子晶体微腔的耦合体系中, 他们观测到了非局域的相互作用, 通过磁场实现了对耦合强度的有效调控, 其中耦合强度可增强至210 μeV, 如图6所示[114].

除了传统的光子晶体微腔外, 最近提出的高阶拓扑绝缘体也为设计更加鲁棒的拓扑光子晶体微腔提供

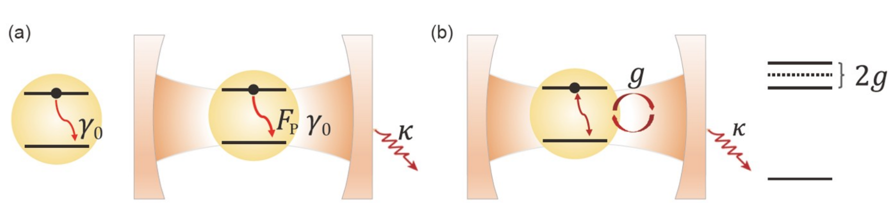

图 3 (网络版彩色)腔量子电动力学. (a) 弱耦合体系下的Purcell增强; (b) 强耦合体系的拉比振荡

Figure 3 (Color online) Cavity quantum electrodynamics. (a) Purcell enhancement in the weak coupling regime; (b) Rabi oscillation in the strong coupling regime

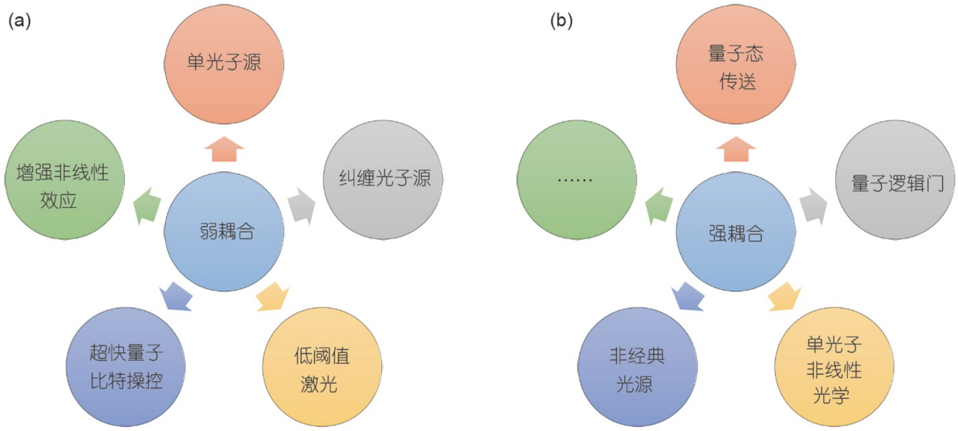

图 4 (网络版彩色)弱耦合体系(a)和强耦合体系(b)的应用前景
Figure 4 (Color online) Potential applications of the weak coupling regime (a) and the strong coupling regime (b)

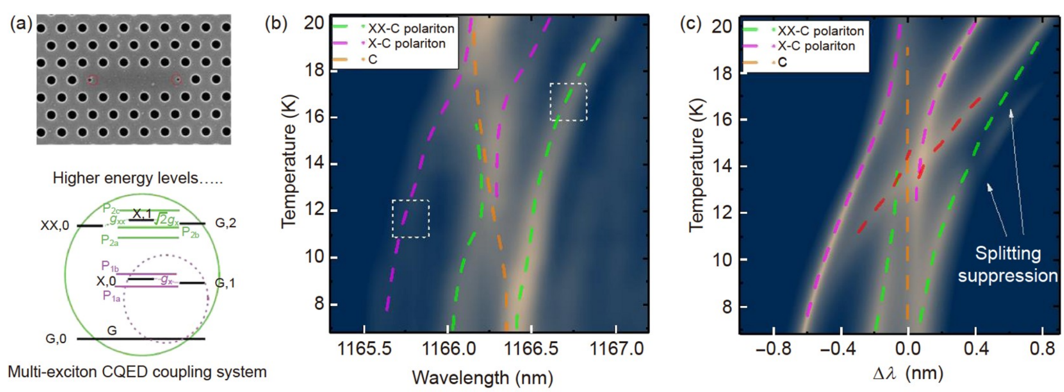

图 5 (网络版彩色)双光子拉比劈裂[113]. (a) 上图: L3型光子晶体微腔, 下图: 微腔与多激子态耦合体系的能级示意图; (b) 双光子拉比劈裂实验结果; (c) 双光子拉比劈裂计算结果
Figure 5 (Color online) Two-photon Rabi splitting[113]. (a) Upper picture: Photonic crystal L3 cavity; lower picture: Energy level of the multiexciton-cavity coupling system; (b) experimental results of the two-photon Rabi splitting; (c) calculation results of the two-photon Rabi splitting

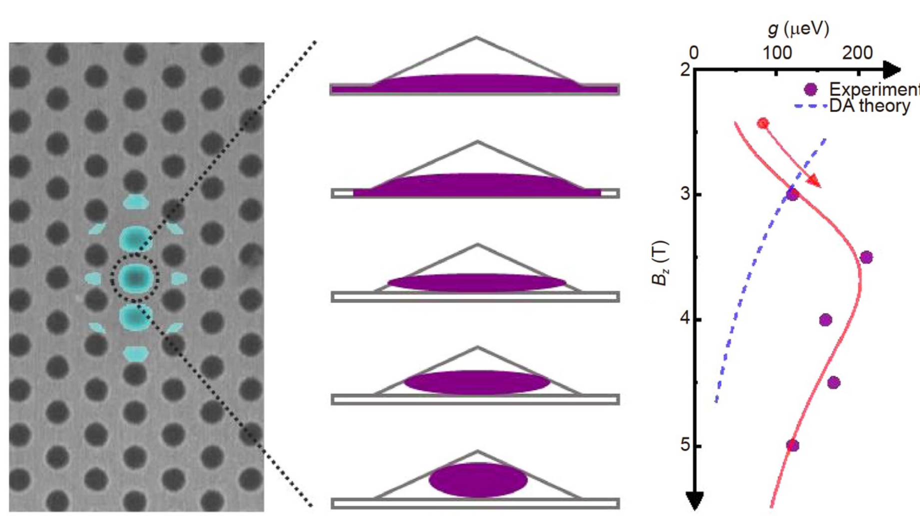

图 6 (网络版彩色)光子晶体微腔与量子点p壳层激子的强耦合体系[114]
Figure 6 (Color online) Strong coupling regime between photonic crystal cavities and p-shell excitons in quantum dots[114]

了可能. 基于广义的2D Su-Schrieffer-Heeger模型, 可以设计二阶拓扑光子晶体. 根据体边角对应关系, 在这种结构中存在着高度局域的拓扑角态, 并且已经在光学波段实现[115]. 通过结构优化, 这种拓扑角态的品质因子理论值可以优化到10^4, 实验值可以达到10^3, 并且通过与量子点集成, 实现了拓扑角态对单量子点的Purcell增强[116]和低阈值拓扑激光[117]. 这种量子点与拓扑微腔的耦合体系为研究更加鲁棒的腔量子电动力学体系、发展拓扑纳米光学器件提供了很好的基础.

4 总结与展望

自组织生长量子点与光子晶体微腔的耦合体系在近20年中取得了重要的研究进展, 大大丰富了腔量子电动力学的研究以及促进了量子信息科学领域的发展. 这种耦合体系为研究腔量子电动力学以及发展规模化的量子网络提供了一个很好的平台和载体. 但是, 目前距离它的实际应用还面临一些问题, 比如自组织生长量子点的能量、位置、偏振等的随机性以及光子晶体微腔结构的脆弱性等. 因此, 未来一方面可以优化或发明新型量子点生长方法, 实现量子点的可控生长, 或者可以通过多种成像手段实现量子点的精确定位; 另一方面需要优化光子晶体微腔的结构和制备过程, 实现具有更高性能、更为鲁棒的光学微腔, 从而为其实际应用及发现更多新奇的物理现象提供平台. 除此之外, 该体系的集成化和规模化发展也是未来的主要研究方向.

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Summary for “量子点与光子晶体微腔的耦合”

Coupling between quantum dots and photonic crystal cavities

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Cavity quantum electrodynamics studies the interaction between light and matter at the single quanta level, i.e., cavity photons and quantum emitters, which has widespread applications in quantum information processing and optical devices, such as lasers, solar cells and light-emitting diodes. To study cavity quantum electrodynamics, a quantum emitter with excellent quantum properties and a cavity with high quality factor and small mode volume are preferred. The coupling between self-assembled quantum dots and photonic crystal cavities has attracted broad attention due to the advanced semiconductor fabrication techniques and excellent optical properties. Great progress has been made in the last two decades, which provides an efficient quantum interface between light and matter at the near-infrared domain.

The self-assembled quantum dots have excellent optical properties, including high brightness, high single photon purity, and high indistinguishability, possessing great advantages in the applications of laser, single-photon source, entangled photon source and quantum bit. On the other hand, photonic crystal cavities have high quality factor and small mode volume, providing strong optical confinement. It can greatly enhance the interaction between light and matter. By coupling to photonic crystal cavities, the optical properties of quantum dots can be strongly modified. For example, in the weak coupling regime, where the coupling strength g is smaller than the decay rate of the system, the spontaneous emission rate of quantum dots is enhanced due to the increase of local density of states. The enhancement factor, known as Purcell factor, is proportional to the quality factor and inversely proportional to the mode volume of the cavity. The weak coupling can be used to optimize the performance of optical devices, such as reducing the laser threshold, increasing the efficiency of single-photon source and entangled photon source. In the strong coupling regime, where the coupling strength g is larger than the decay rate, the energy shifts back and forth between quantum dots and cavity modes at vacuum Rabi frequency, leading to the formation of exciton-polariton with Rabi splitting about $2g$. The strong coupling has been widely proposed for the applications in quantum information processing and investigation of nonlinear optical effects at single photon level, such as the realization of quantum logical gate, the operation of qubit, the transfer of quantum states and single-photon blockade. Additionally, photonic crystal structures have a high level of integration. By integrating with waveguides, the coupled system, served as quantum nodes, can be connected to achieve the quantum internet. Besides the traditional photonic crystal cavities, recently a new type of cavity with topological origin has been proposed and demonstrated, providing a more robust platform to investigate cavity quantum electrodynamics and develop optical devices with built-in protection for topological nanophotonic circuitry.

In this paper, we review the basic principle and recent progress of the coupling between self-assembled quantum dots and photonic crystal cavities, which show a great opportunity to realize various optical devices with diverse functionalities, providing an ideal platform to realize on-chip photonic circuitry.

quantum dots, photonic crystal cavities, cavity quantum electrodynamics, strong coupling, weak coupling

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