Highly Reduced Fine-Structure Splitting in InAs/InP Quantum Dots Offering an Efficient On-Demand Entangled 1.55-μm Photon Emitter

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To generate entangled photon pairs via quantum dots (QDs), the exciton fine-structure splitting (FSS) must be comparable to the exciton homogeneous linewidth. Yet in the $(\mathrm{In,Ga})\mathrm{As}/\mathrm{GaAs}$ QD, the intrinsic FSS is about a few tens $\mu\mathrm{eV}$. To achieve photon entanglement, it is necessary to cherry-pick a sample with extremely small FSS from a large number of samples or to apply a strong in-plane magnetic field. Using theoretical modeling of the fundamental causes of FSS in QDs, we predict that the intrinsic FSS of $\mathrm{InAs}/\mathrm{InP}$ QDs is an order of magnitude smaller than that of $\mathrm{InAs}/\mathrm{GaAs}$ dots, and, better yet, their excitonic gap matches the $1.55\ \mu\mathrm{m}$ fiber optic wavelength and, therefore, offers efficient on-demand entangled photon emitters for long distance quantum communication.

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Entangled photon pairs distinguished themselves from the classically correlated photons because of their nonlocality [1,2] and therefore play a crucial role in quantum information applications, including quantum teleportation [3], quantum cryptography [4], and distributed quantum computation [5]. Benson et al. [6] proposed that a biexciton cascade process in a self-assembled quantum dot (QD) can be used to generate the ‘‘event-ready’’ entangled photon pairs, with orders of magnitude hif4TJ001scn16.92550TD(1(b))Tj000scn1.66380TD[(].)-262.5(The)-260(small)]TJ-18.5893-1.14

The reason for the early optimism about the use of QD for generating entangled photon pairs stems from the thought that FSS of an exciton will vanish [see Fig. 1(a)] in shape-symmetric (e.g., cylindrical) dots [14]. However, the FSS of an exciton in a dot contains two terms: the previously largely ignored ‘‘intrinsic FSS’’ [14], which is nonzero even in a shaped-symmetric dot, and the ‘‘shape-asymmetric FSS’’ due to deviation from geometric symmetry along the [110] and $[1\bar{1}0]$ directions [12]. In this sense, the FSS is just like the spin-splitting effects, which are composed of the intrinsic Dresselhaus term [15], due to the bulk inversion asymmetry, and the Rashba term [16], due to the geometrical asymmetry. Whereas the contribution to the FSS of QD shape asymmetry [12] can be reduced by carefully controlling the growth conditions, the ‘‘intrinsic’’ FSS is still present even for an idea cylindrical dot, because semiconductor materials from which dots are commonly made have the zinc-blende structure and are thus not spatially isotropic. The zinc-blende structure has T_d symmetry, so even a cylindrically shaped, i.e., lens or cone, QD made of a zinc-blende semiconductor can only have a subgroup C_{2v} symmetry [17]. Since the interface between the dot material and the surrounding matrix material is not necessarily a reflection plane, the (atomistic) potentials are different along the [110] and $[1\bar{1}0]$ directions [17], leading to a natural, built-in intrinsic FSS electron and holes states (including spin), which converge very well with the results. Since the exciton and biexciton are nearly linearly polarized along the [110] direction and the [1$\bar{1}$0] direction [19], the FSS is defined as the energy splitting between the [110] polarized exciton and [1$\bar{1}$0] polarized exciton, i.e., $\square_{\mathrm{FSS}} = E(X_{[110]}) - E(X_{[1\bar{1}0]})$.

Figure 3 shows the FSS in these two systems as a function of the excitonic energy [23]. The exciton energies of the cone-shaped dots are similar to that of the lens-shaped dots.

Effect of shape asymmetry to FSS.—Figure 4(e) depicts the FSS of the InAs/GaAs QDs as functions of the lateral aspect ratio $R_{[110]}/R_{[1\bar{1}0]}$, whereas Fig. 4(f) shows the results for the InAs/InP InP