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Signature of Superconducting Density of States in Luminescence Spectra of InAs Quantum Dots

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Abstract:

We report the observation of signature of superconducting density of states (DOS) in the luminescence spectra from InAs quantum dots (QDs) for the first time. Cooper pairs penetrate from a niobium (Nb) superconductor to an adjacent n-type InGa(Al)As heterostructure with the proximity effect. The luminescence is rate-limited by the population of minority holes injected with photo-excitation. The QD luminescence intensity was enhanced more than 3 times below the superconducting critical temperature. This advances a step toward realizing the superconductor-based QD light-emitting diode (SQLED) that we proposed previously for generating entangled photon pairs (EPPs).

1. Introduction

Superconducting (SC) qubits have been actively studied and are regarded as the most prominent candidate for future applications to quantum information and communication (QIC) [1]. In SC states, electrons form Cooper pairs and change from fermions to bosons. Their spin singlet states are regarded as entangled electron pairs and there have been active studies to split them and extract entangled electrons to normal electrodes [2,3].

For the QIC applications, solid-state qubits have to be converted into photon qubits for long-distance communications. Especially EPPs play important roles for quantum teleportation [4] and entanglement swapping [5] which are necessary for realizing quantum repeaters. EPP sources employed up to now to these experiments have been limited to parametric down conversion based on optical nonlinearity [6]. Solid-state EPP sources based on semiconductor QDs have been actively studied, but they generate time-cascaded photon pairs and the photon sources for simultaneous EPP generation necessary for such applications are missing at present.

In this regard, we proposed a superconductor-based QD light emitting diode (SQLED) to generate EPPs on demand [7]. This is a conversion of the entangled electron pairs to EPPs via the radiative recombination in a QD. Since the Cooper pairs are bosons, their number states are not fixed. In the SQLED, the number of holes to recombine with electron Cooper pairs is regulated with the valence-band QD ground state population via the Pauli's exclusion principle. This makes it possible to generate on-demand EPPs.

In our previous experiments, we demonstrated Cooper-pair-based luminescence enhancement below the SC critical temperature (T_C) [8, 9]. However in our previous experiments, no SC properties were observed in luminescence spectra [10], which have been expected in theory [11]. In this paper, we study luminescence of an InAs QD heterostructure that is in contact to a Nb superconductor and report the observation of the signature of the SC DOS in the luminescence spectra from InAs QDs below the SC critical temperature.

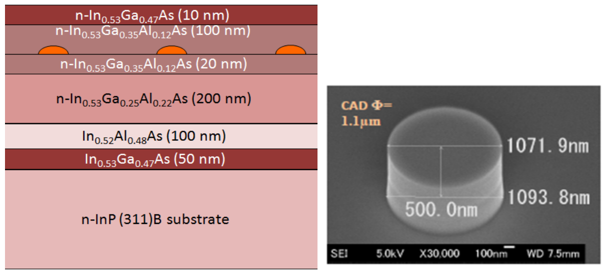

Fig. 1. InAs QD heterostructure grown on (311)B InP substrate and its pillar structure prepared with ICP-RIE.

2. Sample preparation

The semiconductor heterostructure was grown on a (311)B InP substrate with molecular-beam epitaxy. The growth was initiated with 50-nm-thick $In_{0.53}Ga_{0.47}As$/ 100-nm-thick $In_{0.52}Al_{0.48}As$ layers for selective etching of

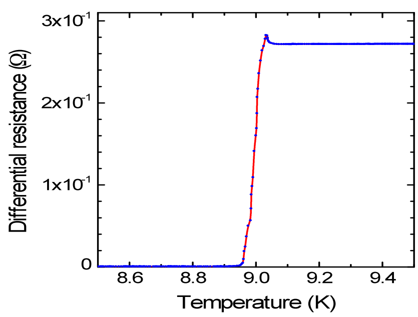

Fig. 2. Temperature dependence of differential resistance measured on the evaporated Nb layer, showing SC T_C=8.97 K.

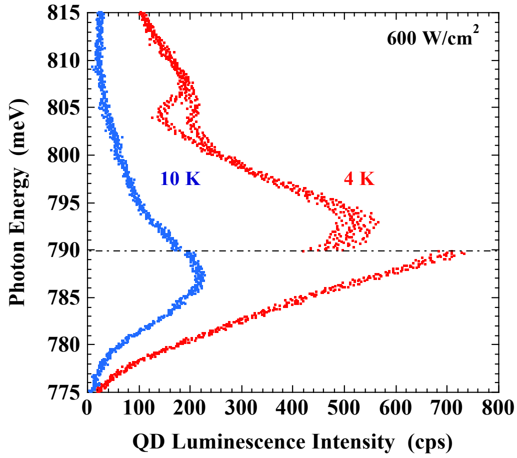

Fig. 3. Luminescence spectrum of QDs measured below and above T_C of ~9.0 K. Excitation power is 600 W/cm^2.

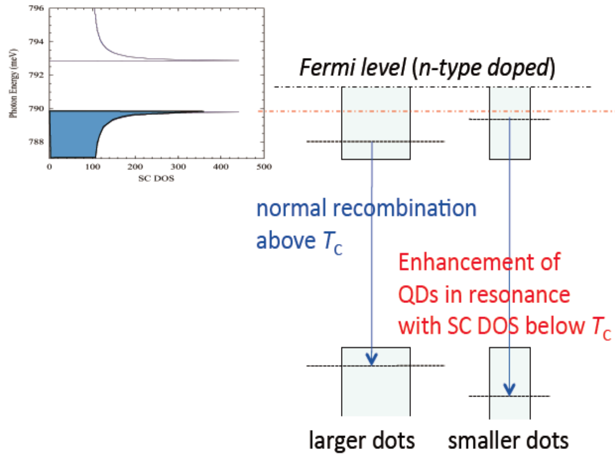

Fig. 4. SC gap opens near the Fermi level in the n-type doped heterostructure, and luminescence of QDs with their conduction-band discrete states in resonance with SC DOS is enhanced below SC T_C.

the InP substrate, followed by a heterostructure of 200-nm-thick n-$In_{0.53}Ga_{0.25}Al_{0.22}As$/ 20-nm-thick n-$In_{0.53}Ga_{0.35}Al_{0.12}As$/ 5-monolayer (ML) of InAs QDs/ 100-nm-thick n-$In_{0.53}Ga_{0.35}Al_{0.12}As$/ 10-nm-thick n-$In_{0.53}Ga_{0.47}As$ layers as shown in Fig. 1. The sample surface was etched into a periodic array of pillars with different diameters ranging from 200 nm to 2 μm and the pillars height was about 700 nm. A 200-nm-thick Nb was evaporated on the pillars surface and the whole surface was covered with ~1.5 μm-thick silver (Ag). Then a supporting substrate was pasted to the Ag surface and the InP substrate was removed with mechanical polishing, ICP-RIE, and chemical etching. SC property of the Nb layer was examined and T_C of ~9.0 K was confirmed as shown in Fig. 2.

3. Luminescence Measurements and Discussion

Temperature dependence of the luminescence was measured with a micro-luminescence setup employing He-Ne laser excitation at 632.8 nm. We observed three major peaks at 0.79 eV, 0.93 eV and 1.16 eV, which were identified to be originated from the InAs QDs, $In_{0.53}Ga_{0.35}Al_{0.12}As$ and $In_{0.53}Ga_{0.25}Al_{0.22}As$ barriers, respectively. Here we focus to the luminescence spectra measured from InAs QDs as shown in Fig. 3. The luminescence intensity at 4 K is about three times higher than that at 10 K, and the intensity showed abrupt increase below the SC T_C (not shown), which is reproducible with the previous results [8,9]. This shows that the luminescence below T_C is the one of Cooper pairs. Electron Cooper pairs are injected from the Nb superconductor into the n-type $In_{0.53}Ga_{0.35}Al_{0.12}As$ barrier layer and the modulation-doped InAs QDs along the Fermi level by the proximity effect.

A noticeable feature in Fig. 3 is the presence of a "sharp edge" at 790 meV at 4 K, which disappears at 10 K above T_C. It is also noted that the luminescence peak is red shifted at 10 K. This result is interpreted in Fig. 4. QDs luminescence peak is population dependent. Under the normal condition at 10 K, the peak is below 790 meV. Below the SC T_C, QDs whose conduction-band energy states are in resonance with the SC DOS are enhanced in their recombination with holes in the valence-band due to the electron Cooper pairs condensed in the SC DOS [11]. This results in the sharp luminescence peak at 790 meV at 4 K in Fig. 3. The emission spectra above 790 meV may be related to quasi-particle excitation above the SC gap, but it is still under study. The observed temperature-dependent "sharp edge" manifests the first signature of the SC DOS in spontaneous luminescence spectra, and this forms the firm foundation for realizing the SQLEDs in near future.

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