Quantum wire networks for superconducting quantum-dot superlattices

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Abstract

Quantum wire networks have been proposed for fabricating quantum-dot superlattices with the square and the plaquette lattice structures. These artificial lattices are well represented by Hubbard models with parameters determined by the local density approximation. The superconducting transition temperature T_c (=90 mK) for the plaquette lattice is more than two times T_c (=40 mK) for the square lattice and is sufficiently high for achieving superconductivity in experiments.

Key words: superconductivity, quantum dot superlattices, quantum wire networks, Hubbard models

The lattice structure and the electron filling are governed by the atomic nature in solids. By contrast, in quantum-dot superlattices (QDSL), we can have desired lattice structures by putting quantum dots (QD) as artificial atoms on the lattice points, and also have desired electron filling by controlling the gate voltage. In QDSLs, we can study interesting phenomena such as ferromagnetism [1–4] and superconductivity originating from the Coulomb interaction between electrons. In fact, Shiraishi et al.[5] have proposed a ferromagnetic QDSL designed on a quantum wire network. Recently, it has become possible to fabricate a regular QDSL in actual experiment. For instance, the quantum Hall effect in a lateral periodic potential has also been reported [6], which is a clear evidence of lattice formation and phase coherence over unit cells.

In this paper, we propose a design of quantum wire network for a QDSL with a square or plaquette lattice structure [Fig. 1(a)]. In the plaquette lattice, the lateral distance between adjacent wires is slightly modulated. In the quantum wire network, a localized state is formed at the intersection of the wires because of the coherence between the crossed plane waves. The localized states are coupled with each other to form QDSLs that can be well represented by Hubbard models. We study superconducting transition temperature (T_c) for the Hubbard models and show T_c for the plaquette QDSL is more than two times that for the square QDSL, and reaches 90 mK which is reasonable for achieving superconductivity in experiments.

We assume InAs quantum wires surrounded by an $In_{0.776}Ga_{0.224}As$ barrier with a band offset of 0.17 eV [7]. The width and the height of each quantum wire are 50 nm. The lateral distance between adjacent wires is 61.1 nm for the square lattice. For the plaquette lattice, the lateral distances between adjacent wires are

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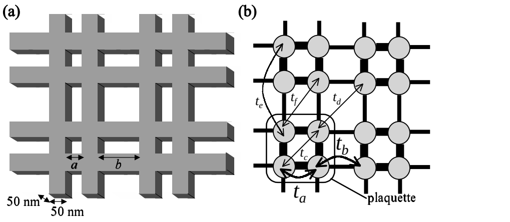

Fig. 1. Our quantum wire network (a) and the corresponding tight-binding model with hopping integrals (b).

alternated with the narrower (wider) distance a=38.8 (b=83.4) nm. These parameters are carefully determined; if they are too small, the wave function of the electrons is not well localized on a QD and the system becomes an electron gas, while if they are too large, the hopping parameter between adjacent QDs, to which T_c of the superconducting transition is in proportion, becomes very small. The band structures of the wire network are calculated using first-principles calculations based on a local density functional approximation (LDA) with the Perdew-Zunger exchange-correlation potential [8]. The LDA band diagram can be perfectly fitted to the tight-binding calculation for the square or plaquette QDSL. The fitting parameters, which are depicted in Fig. 1(b), are as follows: $t_a = t_b = 0.179$, $t_c = t_d = t_f = -0.017$, and $t_e = -0.021$ for the square QDSL, whereas $t_a = 0.242$, $t_a = 0.242$, $t_b = 0.151$, $t_c = 0.003$, $t_d = -0.025$, $t_e = -0.024$, and $t_f = -0.014$ for the plaquette QDSL (The unit is milli-electron volt). The intra-dot interaction, estimated by subtracting the Ewald sum for inter-dot interactions from the total Hartree energy, is U =1.8 meV (1.7 meV) for the square (plaquette) QDSL.

We study the superconducting transition by employing the fluctuation-exchange (FLEX) approximation [9] along with the Eliashberg equation on the Hubbard model with the above fitting parameters. The FLEX approximation is a self-consistent random phase approximation, which is known to be appropriate for treating strong anti-ferromagnetic spin fluctuations. We assume the filling of electrons to be n=0.8 (=the number of electrons/number of dots), where we can avoid anti-ferromagnetism near half-filling (n=1), and at the same time obtain strong enough spin fluctuation to achieve a high T_c. As a result, we obtain T_c=90 mK for the plaquette QDSL and T_c=40 mK for the square QDSL. The mechanism of the big enhancement in T_c for the plaquette QDSL is due to the disconnectivity of the Fermi surfaces and is similar to the mechanism recently proposed by Kuroki and Arita [10]. Figure 2 shows the enhancement of T_c when hopping parameters t_a and t_b are changed with $n = 0.85$, $U = 7$, $t_c = t_d = t_e = t_f = 0$. Here, T_c is scaled in units of the averaged hopping parameter $(t_a + t_b)/2 = 1 = W/8$, where W is the single-particle bandwidth. We find that T_c is

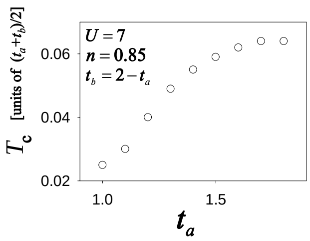

Fig. 2. T_c plotted as a function of t_a in units of the averaged hopping parameter $(t_a + t_b)/2 = 1$. Here, the single-particle bandwidth is given by $4(t_a + t_b) = 8$. The parameter $t_a = t_b = 1$ (which corresponds to the square lattice) gives $T_c = 0.025$

enhanced as the difference between t_a and t_b becomes larger, and that T_c for $t_a = 1.5$ and $t_b = 0.5$ is more than two times that for the square lattice ($t_a = t_b = 1$).

Finally, we note that if cuprates in a plaquette type lattice can be achieved in the future, the high T_c may be near room temperature, because T_c for the plaquette lattice is more than two times that for the square lattice, which is a model for the now existing high T_c cuprates.

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