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Possibility of Magnetic Ordered States in Semiconductor Quantum Dot System

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Recent progress in semiconductor technology enables us to construct ultra-fine structures such as zero dimensional quantum dots[1]. While many of the excellent properties of fine structure devices are based on modulated electronic state caused by the quantum confinement for electrons on a site, we can expect another feature from them, the enhancements of electron-electron interaction and the electron correlation due to stronger electron confinement. This suggests the possibility of realizing, in semiconductors, the electronic properties that are based on the many body effect, such as ferro-magnetic state and superconductivity. This paper describes the possibility of magnetic ordered states in the GaAs/AlGaAs quantum dot system, when its structure is designed as revealed here so that the electrons are strongly correlated.

Subband energy levels are calculated for box-shaped GaAs/$Al_xGa_{1-x}As$ quantum dot, as shown in Fig.1 (x=0.45), using the Kronig-Penny model and Marcatili approximation. The difference between the first excited level, E_1, and ground level, E_0, is a decreasing function with respect to dot width w. Repulsion energy U for two electrons sited on the same dot can be estimated by $U = \frac{e^2}{4\pi\epsilon}\int \frac{\psi(\mathbf{r_1})\psi(\mathbf{r_2})}{|\mathbf{r_1}-\mathbf{r_2}|}d\mathbf{r_1}d\mathbf{r_2}$, where ψ is an electron wavefunction. Since the calculated U value is around tens of meV as shown in Fig.2, the affinity level of ground state E_0+U, which is shown by the broken line in Fig.1, does not exceed the excited level in the region of 50Å$\sim$w$\sim$200Å. Thus, when the quantum dots are arranged with spacing s and the number of electrons is less than twice of the dot number, the system can be described by the one band Hubbard model[2], where only the E_0 level and its affinity level are taken into account. The electron tunneling rate to a neighboring dot is determined by transfer energy t, which is calculated as shown in Fig.3. Since t decreases more rapidly than U and U/t increases as w increases, a strong correlation effect can be expected in the larger w and s regions.

The magnetic properties of quantum dots arranged in three dimensions can be studied using a mean field approximation for the Hubbard model[3], in which para-, ferro-, ferri- and antiferromagnetic phases appear corresponding to different number of electrons. The calculated phase diagram for a GaAs/$Al_{0.45}Ga_{0.55}As$ quantum dot system with a constant ($10^{17}cm^{-3}$) electron density is shown in Fig.4. The hatched and dotted areas indicate the parameter regions where magnetic long range order is obtained. Two dimensional arrangement of the quantum dots also exhibits ferro- and antiferro-magnetic states within the framework of the mean field approximation[4]. Figure 5 is the calculated phase diagram for a two dimensional dot array with a $4\times10^{11}cm^{-2}$ electron density. In both systems, magnetic ordered states can be expected for structures with w or s of 50Å$\sim$ 200Å with reasonable electron densities.

In conclusion, it is found that the GaAs/AlGaAs quantum dot system can be described by the one band Hubbard model, which exhibits a strong electron correlation when w $\gtrsim$ 50 Å. Magnetic orderings such as ferro- and antiferro-magnetism can thus be expected in quantum dot arrays with w or s of 50Å$\sim$ 200Å, when the electron densities are typically $10^{17}cm^{-3}$ and $4\times10^{11}cm^{-2}$ for three dimensional and two dimensional systems, respectively.

References

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3) D.R.Penn; Phys. Rev. **142** (1966) 350.
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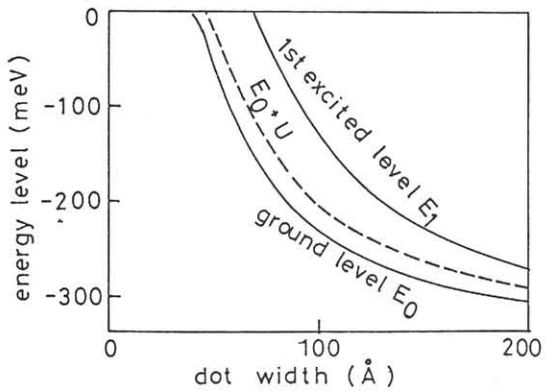

Fig.1: Subband energy levels (solid lines) and affinity level (broken line) for a box-shaped $GaAs/Al_{0.45}Ga_{0.55}As$ quantum dot.

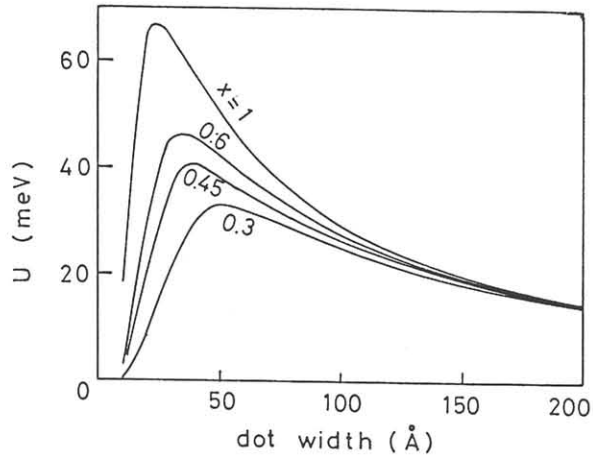

Fig.2: Repulsion energy U for two electrons sited on the same $GaAs/Al_xGa_{1-x}As$ dot as a function of dot width.

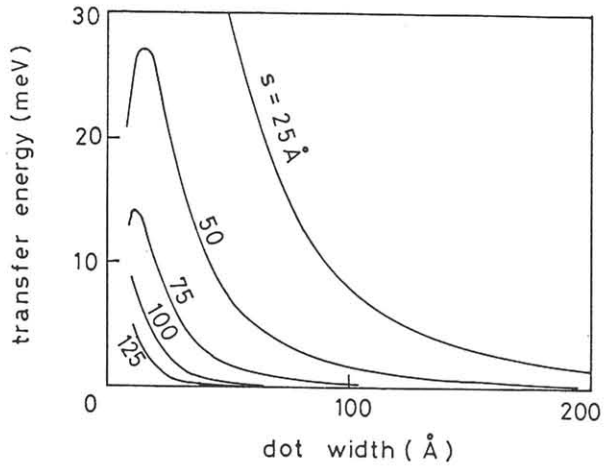

Fig.3: Transfer energy for an electron, sited on a $GaAs/Al_{0.45}Ga_{0.55}As$ quantum dot, tunneling to its neighboring dot. s is spacing between the two quntum dots.

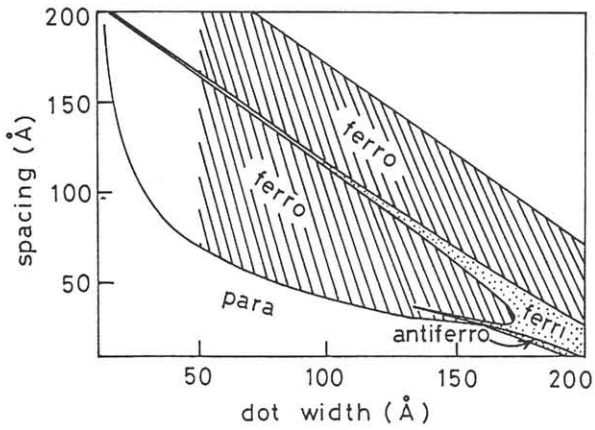

Fig.4: Phase diagram for three dimensional $GaAs/Al_{0.45}Ga_{0.55}As$ quantum dot system with constant ($10^{17}cm^{-3}$) electron density. The hatched region corresponds to ferro-magnetic phase and the dotted to ferri- or antiferro-magnetic phase.

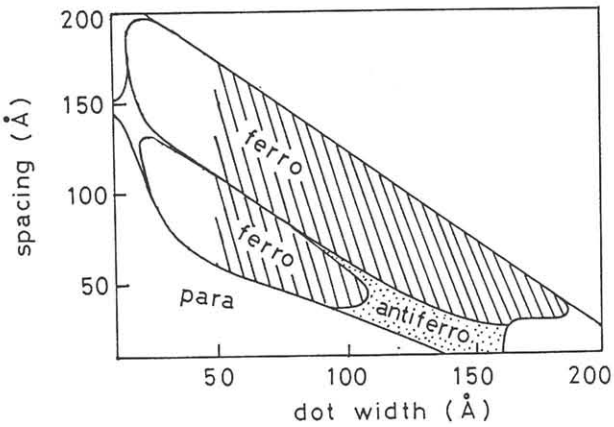

Fig.5: Phase diagram for two dimensional $GaAs/Al_{0.45}Ga_{0.55}As$ quantum dot system obtained under the mean field approximation with constant ($4\times 10^{11}cm^{-2}$) electron density. The hatched region corresponds to ferro-magnetic phase and the dotted to antiferro-magnetic phase.