Section 2 Quantum-Effect Devices

Chapter 1. Single-Electron Electronics

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1.1 Goals and Objectives

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When electrons are confined to a small particle of metal or a small region of a semiconductor, both the energy and charge of the system are quantized. In this way, such nanometer-sized systems behave like artificial atoms.[3] The quantization of energy is familiar: the solutions of the Schrödinger equation in an isolated region have discrete energies. In some ways, however, the quantization of charge is more mysterious. We are quite comfortable with the idea that the charge of a collection of electrons is discrete. However, the charge in any small volume of a large sample of a conductor is *not* discrete because the electronic wave functions are extended over the entire sample. Only when the states are localized is the charge quantized.

Artificial atoms have been constructed using metals and semiconductors; and they have been given a variety of names: single-electron transistor (SET), quantum dot, and zero-dimensional electron gas. The physics of these devices is the same, although the limits in which they operate may be quite different. The goal of our research is to better understand the physics of these devices in order to optimize their performance so that circuit design can begin.

1.2 Summary of Recent Work

We have recently fabricated metal-oxide-silicon single-electron transistors (MOSSETs) which show single-electron phenomena up to 20 K. A single-electron transistor (SET) is an island of charge which is coupled to leads by tunnel barriers. There are two energies that are encountered in changing the electronic state of the SET: (1) the energy required to add an electron to the island, U, and (2) the energy required to excite the electrons already on the island, ΔE. Both of these energies increase as the size of the island is diminished. Since the resolution of single-electron phenomena is limited by the temperature of the electrons, we can increase the operating temperature by reducing the size of the SET. The purpose of our work is to fabricate small SETs and, in addition to achieving higher operating temperatures, to exploit the improved relative resolution to explore coherent interaction between the electrons in the leads and the electrons on the island.

An island of charge can be created by electrostatic depletion of a two-dimensional electron gas (2DEG). By changing the voltages on metallic gates which lie a short distance above a 2DEG, the electrostatic fields can be adjusted; in this way, both the number of electrons on the island and the size of the tunnel barriers can be varied. The size of the island is limited by the depletion width, which decreases as the gates are brought closer to the 2DEG; a small depletion width allows the possibility

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3 M.A. Kastner, "Artificial Atoms," *Phys. Today* 46(1): January 24 (1993).

of a small island. Thus, to make small SETs one needs a material system in which the gates can be brought close to the 2DEG. The Si-SiO_2 MOS system is ideal for this purpose because SiO_2 is a robust insulator; layers as thin as 10 nm have low leakages, high breakdown voltages, and are easily fabricated. We have therefore chosen to fabricate SETs in the silicon MOS system, rather than in the more extensively studied GaAs-AlGaAs system. Previously observed Coulomb blockade (CB) effects in electrostatically patterned MOS structures have resulted from impurities. More recent work[4] has achieved CB in a Si-SiO_2 system using pattern-dependent oxidation. However, our studies were the first to show well-defined CB phenomena in lithographically defined MOSSETs where the tunnel barriers are created by gate electrodes.

Standard silicon fabrication techniques have been used in combination with electron-beam lithography to fabricate MOSSETs, thus taking advantage of existing technology. We have observed periodic conductance oscillations resulting from CB in a MOSSET, with an addition energy U = 15 meV, which corresponds to temperature $T = U/k_B = 175$ K. However, the widely spaced peaks corresponding to these large energies are usually modulated by what appears to be CB peaks with a smaller period. Lack of reproducibility of this fine structure suggests that it results from disorder at the Si/SiO_2 interface.

We believe that these effects of disorder may be controlled by improvement of the interface. Our mobilities are much lower than those that have been obtained elsewhere, so less disordered interfaces are possible. However, our studies may provide a useful new probe of the nature of disorder at the Si/SiO_2 interface, which might be technologically valuable.

1.3 Publications

Abusch-Magder, D.M., M.A. Kastner, C.L. Dennis, W.F. Dinatale, T.M. Lyszczarz, D.C. Shaver, and P.M. Mankiewich. "Coulomb Blockade in a Silicon Mosset." *Conference Proceedings of the NATO Advanced Study Institute on Quantum Transport in Semiconductor Submicron Structures*, 1996.

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[4] Y. Takahashi, M. Nagase, H. Namatsu, K. Kurihara, K. Iwadate, Y. Nakajima, S. Horiguchi, K. Murase, and M. Tabe, "Fabrication Technique for Si Single-Electron Transistor Operating at Room Temperature," *Electron. Lett.* 31: 136 (1995).