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Quantum dots and other mesoscopic systems

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We present a brief description of some of the mesoscopic systems which are of current interest and point out their importance in basic research as well as in tomorrow's technology. We emphasize the need for such research in this country.

Impressive advances in miniaturization

We have recently witnessed a revolution in condensed matter physics. Until recently, this branch of physics has been confined to physical systems that were essentially provided by Nature. However, after quantum wells were first made in the laboratory, it was clear that artificial systems (quantum confined) can be tailored to have unusual and intriguing optical and transport properties. This exciting possibility has now taken a new dimension with the ability to *microfabricate matter* on an unprecedented scale[1]. Utilizing nanofabrication techniques, such as atomically-precise crystal growth and electron beam lithography, it is now possible to literally create any type of structure that one is ingenious enough to conceive, where the *quantum mechanical properties are quite dominant.* Various quantum confined systems, listed below, are well known for their interesting physical properties like:

- Quantum dots (artificial/designer atoms) (zero-dimensional electron systems)—transport, optical and capacitance spectroscopies[1–5],
- Anti-dots (Quantum pinballs) (two-dimensional electron systems)—transport and optical studies[1–2],
- Electron turnstiles (zero-dimensional electron systems)—transport properties[6],
- Quantum rings (one-dimensional electron systems)—observation of the persistent current[2,7],
- Quantum wire superlattices (one-dimensional electron systems)—observation of the collective phenomena[8],
- Semiconductor heterojunctions (two-dimensional electron systems)—observation of the integer and fractional quantum Hall effect (FQHE)[9].

They are created by confining the electron motion in one-, two- and three-dimensions[1–3]. This ability to design new systems is also largely motivated by the eventual application of quantum effects in nanostructures to electronic devices. A commercial application of the two-dimensional electron gas is its use in the high electron mobility transistor (HEMT), which is used in the first stage of satellite receivers. The low noise performance of HEMT at frequencies well above that of other devices has greatly reduced the transmission powers needed. The costs of satellite broadcasting are thereby reduced[10]. It is expected that the quantum confined structures will be widely used in optoelectronics, like in light-emitting diodes and lasers, in fibre-optics communications, optical storage, like the CD players[10]. Other application areas are telecommunications, computers and aerospace. There are also enormous potentials for microlasers[10] in other fields like biology, and even dentistry etc.

Major questions, phenomena

I present below two examples of quantum confined systems which underscore the important message they all convey: basic knowledge as well as potential for applications.

In 1928, Fock[11] studied the problem of a single electron in a parabolic potential and subjected to a perpendicular magnetic field, and after more than sixty years, inter-electron interactions were introduced to that problem[4]. Finally, in 1993, Ashoori *et al.*[5] reported single-electron capacitance spectroscopy in a single quantum dot. Here, electrons tunnel into the dot and change capacitance of the device. That capacitance as function of Fermi energy E_F shows discrete set of almost equally spaced peaks. Peak appears when:

$$E_F = \mu(N) = E_0(N) - E_0(N-1),$$

where μ is the chemical potential and $E_0(N)$ is the ground state energy of N-electron system. The ground state energies of 1–50 electrons in a quantum dot were obtained in this manner. The results show distinct few-electron features (atomic-like) and gradually the FQHE-like many-body features appear as the electron number in the dot is increased. Some of these results are understood (or even predicted), while the other results are yet to be explained.

Electron turnstile. This system, first created by Kouwenhoven *et al.*[6], relies on the discrete charge of an electron. If an electron is allowed to pass between the plates of a microscopic capacitor, the energy provided by the voltage difference has to exceed the minimum charging energy $e^2/2C$, where C is the capacitance. By adjusting the voltage drop across the capacitor, one can control the motion of electrons *one at a time*. This system might turn out to be the ultimate in digital technology because it might become the basis for electronics in which a *bit* of information might be carried by a single electron.

In both these examples, one should appreciate the extreme precision that went into controlling the motion of individual electrons. The literature abounds with many such examples.

Indications that the field is important

There are plenty of signs which indicate that the field is important and rapidly growing:

- Explosion in number of meetings (including prestigious ones like Taniguchi Symposium on Physics of Mesoscopic Systems, Shima, Japan, 1991 and NATO Advanced Research Workshop on Physics of Few-Electron Nanostructures, Delft, The Netherlands, 1992) and publications on mesoscopic systems.
- Increasing attention of major laboratories—There seems to be some activity in almost every world class semiconductor group.
- Decreasing size of industrial semiconductor devices—Sub-micron dimensions are routine and 0.2 micron dimension are being talked about. The basic research in that stage becomes quite important because, it is now generally appreciated that when device sizes reach dimensions similar to the electron scattering length, the physics of electron transport begins to change.
- The status of the field is that there is still a lot of challenging physics to do with potential applications at the end of the road.

The bottom line is, we need to develop fabrication expertise to prepare for smaller scales, and, we need to understand how the physics will help or hinder small device operation or even generate new type of devices.

Situation in India

I am not aware of any group-activities (theory or experiment) in our country on the topics mentioned above. There are, however, some individuals scattered around the country doing quite good work on mesoscopic systems. To coordinate these activities, seminars, workshops, etc. need to be organized on a regular basis.

Future action

In an effort to initiate some activities, we, at the Institute of Mathematical Sciences, Madras are organizing an international meeting on low-dimensional electron systems (9–14 January 1995), where a large number of leading experimentalists and theoreticians from abroad are expected to attend and discuss the developments in the field of mesoscopic physics. It will give young researchers in India the necessary exposure to the activities by world-class researchers in this rapidly developing field. It will also help to promote future collaboration between the participants.

I believe there should be more theoretical activity in this country. A large amount of computational work will be needed for this purpose because, in order to be able to explain the current experimental results, we need to get more precise information than analytical models can deliver. At the same time, we also need to train ourselves for the future miniature devices like quantum dots which, as some people put it, are 'tomorrow's transistors'. Therefore, most importantly, attempts should also be made to create experimental groups on nanostructures. Major funding agencies should support activities of this sort by providing funds to research institutions where these projects are proposed. For experimental projects, we should consider having a center—like a national nanofabrication facility. In this context, I should mention that, several developed countries have Institutes devoted to microstructural studies like:

- AT & T Bell Labs, IBM, Bellcore, etc., US
- Institute for Microstructural Sciences, National Research Council of Canada
- Max-Planck-Institute for Solid-State Research, Stuttgart, Germany; A new Max-Planck-Institute for Microstructural Sciences, Germany

– Delft University of Technology, The Netherlands etc.

In some of these institutions, excellent collaborations exist with the Industries in the areas of optoelectronics and microelectronics[12]. Government support of these endeavours is usually quite generous in many developed countries. I would like to cite some examples of how other Governments are supporting their own research in nanostructures:

- The Ministry of International Trade & Industry in Japan has pledged $ 225 million over the next 10 years on developing nanotechnology; The Japanese Government funds promising researchers through the 'Exploratory Research for Advanced Technology (ERATO)' programme,
- The ESPRIT or RACE programmes of the European community.

Against this backdrop it would be worthwhile for our Government to support the research in microstructural sciences. It would be certainly wise to think in terms of an Institute devoted to experimental and theoretical studies of microstructures.

Finally, in order to start a new facility for microstructural studies, one needs the essential components like: (a) MBE machines to grow substrates, (b) characterization facilities, (c) lithography facilities, and (d) other experimental facilities, like dilution refrigerators, high field magnets, lasers, computers, etc. A rough estimate of the total cost for such a project would be $5–10 million.

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Low temperature facilities for condensed matter research

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The necessity for setting up low temperature facilities, which will be accessible to scientists working in the area of condensed matter physics in universities, is emphasized in this paper. A minimum list of plants and equipment and an estimate of the cost of establishing such facilities are presented. Some suggestions for effective operation of such facilities are also made.

In the past twenty-five years the volume of work in condensed matter physics has increased enormously worldwide. New and interesting discoveries have been made in this field with surprising regularity. In India also the volume of research in condensed matter physics has been growing. While the quantity of work in condensed matter has grown, one cannot say the same of the quality, especially of experimental research. It is true that there are a few institutions in India in which good experimental research is being conducted. But they are a few cases in a barren desert. I am convinced that experimental research will flower in the long run only if the majority of workers in the field, who are in the universities, are provided certain minimum facilities for meaningful work. One such essential facility is for research in low temperature physics.