Formation and Manipulation of Semiconducting and Metallic Nanostructures

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Abstract:
In this presentation will be described novel approaches towards nanofabrication for the realization of room-temperature quantum devices. The presentation is devided into three main sections: the first dealing with the controlled fabricaion of nanocrystals of metallic or semiconducting type, the second describing extreme lithography including nano-scale manipulation of nanocrystals by atomic force microscopy, and the third containing a description of how real-time measurements of electrical device characteristics allow us to controllably make quantum devices which operate at room temperature.

Introduction:

In the strive to realize quantum devices which may operate at room-temperature, one crucial aspect is to make the relevant energy quantization, due to either single electron charging or due to quantum confinement, be large compared with the thermal energy, kT. In order for energy quantization in semiconducting quantum dots to exceed kT this, typically, requires confining structures to be smaller than about 10 nm, and similar requirements hold for devices relying on single electron Coulomb blockade, in order for $E_c = e^2/2C$ to be much larger than kT. It is rather clear that straight forward lithography will not easily solve this problem and, therefore, novel approaches towards nanostructure fabrication and manipulation are needed.

In this talk I will describe an approach to controllably make quantum devices, based on:
(i) controlled fabrication of monodisperse nanocrystals and nanostructures,[1]
(ii) pre-defined contacting and gating metallic structures, made by electron beam lithography, metallization and lift-off, resulting in contact distances controlled to around 10-50 nm,
(iii) atomic-force microscopy for imaging and manipulation of nanostructures,[2] and
(iv) measurement of electrical characteristics of devices during the manipulation of particles.[3,4]

Fabrication of nanocrystals:

In the first part of my talk a fabrication approach towards making monodisperse nanoparticles in metallic as well as semiconducting materials will be described. Results will be presented for different metallic nanoparticles, like silver and indium, as well as for compound semi-conductor nanocrystals, e.g. gallium arsenide and indium phosphide, all of these particles being in the size-range 5 - 30 nm in diameter. The principle of the "Aerotaxy" -process for fabrication of compound nano-crystals is illustrated in Fig. 1.

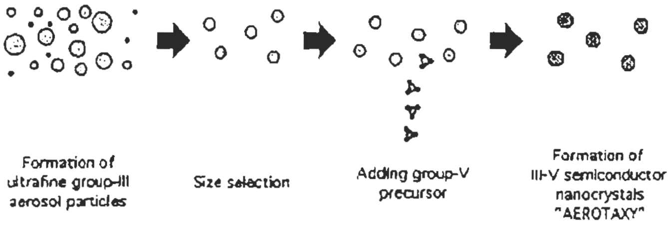

Fig.1

An example of controlled transformation of mono-disperse Ga-drops into monodisperse GaAs from the interaction between AsH_3 and the Ga drops is shown in Fig. 2.

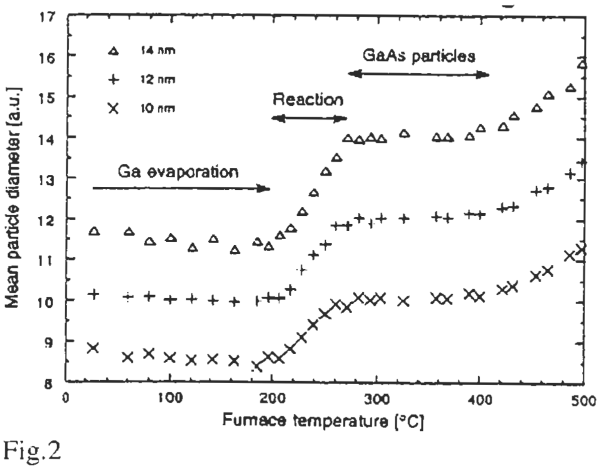

Fig.2

In Fig. 3 we show an example of a 5 nm diameter InP nano-crystal fabricated by the Aerotaxy method, imaged by TEM.

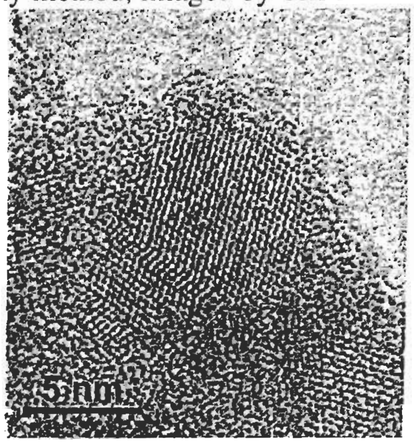

Fig.3

Manipulation of nanoparticles by AFM:

In the second part I will describe the technique we have developed for combined imaging and manipulation of nano-particles as small as 5 nm, using an atomic force microscope (AFM). For this the tip of a conventional silicon AFM cantilever is used as a substrate on which is grown a "super-tip" by depositing a strong carbon tip in a scanning electron microscope. After further processing this tip can reach a sharpness of less than 5 nm in radius. This sharp tip allows very small particles to be imaged and manipulated without unwanted pick-up of particles by the tip. An example of this technique is shown in Fig. 4 in which GaAs nano-crystals are manipulated on the surface of a GaAs wafer.

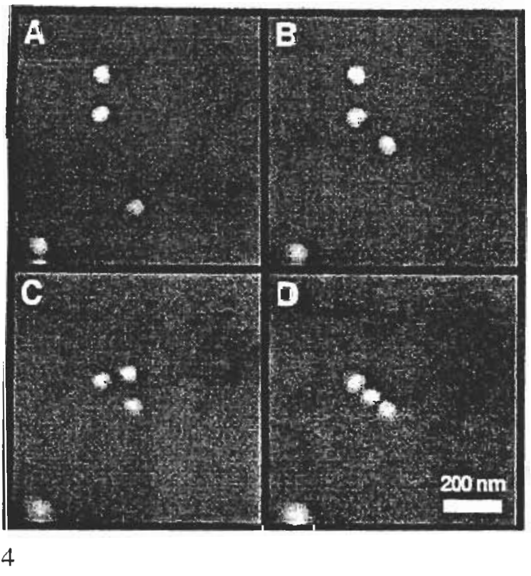

Fig.4

Real time measurement of formation of quantum devices:

In the third part I intend to present device data for two types of quantum devices, namely for single-electron tunneling devices obtained with conducting aerosol particles with insulating shells manipulated in-between metallic electrodes, exhibiting Coulomb blockade behaviour, and for metallic quantum point contact (QPC) devices which can be built with Ångström-level control by which room-temperature operating QPCs with stable conductance levels of $G=n \times 2e^2/h$ can be made. A close-up of the regions between two electrodes with a gold particle which is slowly manipulated into the gap region is shown in Fig. 5.

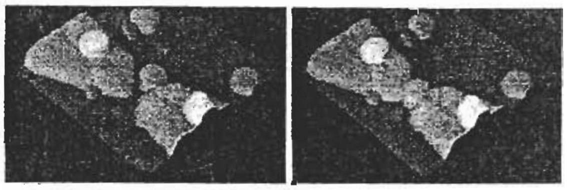

Fig.5

We show first below (Fig. 6) how it is possible to repeatedly create a nano-mechanical switch, by moving a gold nano-particle into and out of the gap between pre-fabricated electrodes.

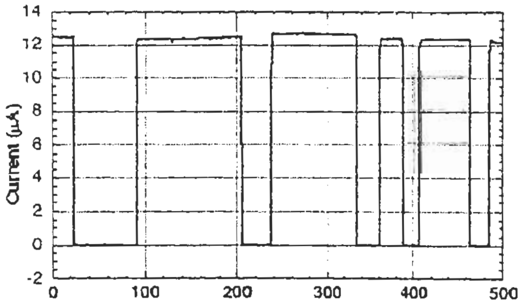

Fig.6

A dynamical measurement of the formation or breaking events reveal that the conductance is indeed quantized when the connecting points are extremely narrow - on the nm-scale. An example of this is shown in Fig. 7 for the dynamical creation of a nano-wire connecting the two gold surfaces. The occurrence of 1 and 4 lateral modes effectively contributing 2e2/h each to conductance may reflect stable geometrical arrangements of Au atoms in the junction.

Finally we show in Fig. 8 below examples of controllably fabricated quantized conductance

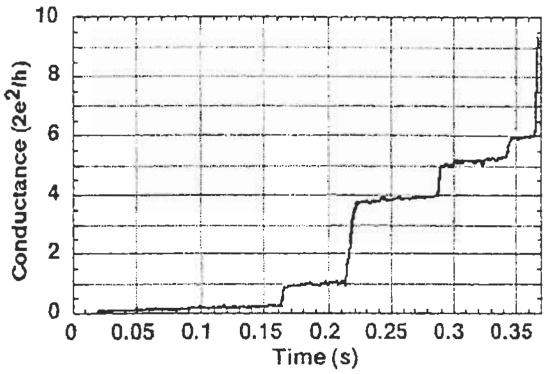

Fig.7

devices which, even at room temperature, are stable for long times (up to several hours) with the conductance on the levels $G = n \times 2e^2/h$.

These results suggest that the manipulation of nano-particles with simultaneous monitoring of device properties allow control in the lateral dimensions better than the Fermi wavelength in gold, or on the level of one Ångström.

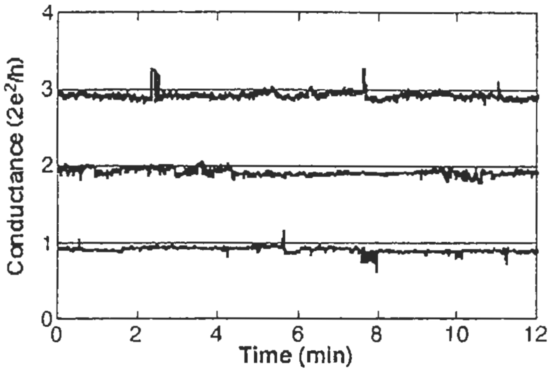

Fig.8

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