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SCANNING TUNNELING MICROSCOPE IMAGES OF IDENTIFIABLE QUANTUM DOT DIODES

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We report the first high resolution images of quantum dots at identifiable locations. They were obtained using a scanning tunneling microscope guided by a novel optical viewing system.

I. INTRODUCTION

Positioning a probe for measurements of a submicrometer area at a desired address in a macroscopic sample is a difficult and important task in nanostructure development. An example is the scanning-tunneling-microscope (STM) characterization of an individual heterostructure whereby both geometry and electrical characteristics can be obtained. Using commercially-available x-y translators equipped with optical encoders, the STM probe can be translated from its initial position (the origin of coordinates) to within 100 nm of a desired address. Since the typical x-y scan range of an STM tip scanner is 1 μm or greater, this coarse-positioning accuracy is more than sufficient for positioning the tip relative to the origin. The extant problem to be solved is thus the initial positioning of the STM tip at the desired location of the origin.

We have solved this problem using a novel initial-positioning apparatus guided by an optical system that permits viewing of the sample and tip with variable magnification up to about 2000. With this system, the STM tip can be positioned at a desired origin to within 1 μm. If the sample has a conducting feature, such as an electron-beam alignment mark, the tip can then be more precisely positioned to the origin by STM scanning. Using this apparatus, we have obtained the first high resolution images of quantum dots at desired, identifiable locations as opposed to images of dots at macroscopically-unknown locations.

II. EXPERIMENT

Our long range scanning tunneling microscope (LRSTM) was developed to provide macroscopic scanning range with nanometer resolution in order to characterize structures such as quantum dots. The LRSTM is a combination of coarse-approach and fine-approach units mounted at a fixed distance from each other. The coarse-approach system is mounted underneath the sample and moves it, while the fine-positioning system is mounted above the sample and provides the STM tip scanning.

Coarse positioning is achieved using manual and piezoelectric translation of the sample. This system, which is represented by the (x,y,z) sample translation stages in Fig. 1, is capable of providing a scanning range of 25.4 mm with a step size of 10 nm. Guidance for coarse positioning is provided by an optical viewing system[1] that mainly relies on the transmission of whole images through a single optical fiber. The optical-fiber input face can

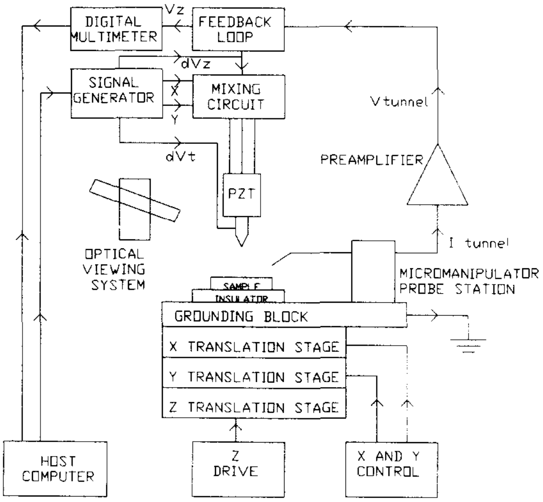

Figure 1: Long Range Scanning Tunneling Microscope block diagram.

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be brought near enough to the STM tip-to-sample junction to see the tip's location on the sample. The fine positioning, which is capable of providing x-y scan ranges of 2 μm × 2 μm with nanometer resolution, is achieved using a piezoelectric segmented-tube tip scanner[2] calibrated by an optical-beam-deflection technique[3]. The entire assembly rests on top of a vibration-isolation/damping system. Furthermore, the STM is operated in air allowing easy access to the sample and tip. A block diagram of the control electronics is also shown in Fig. 1.

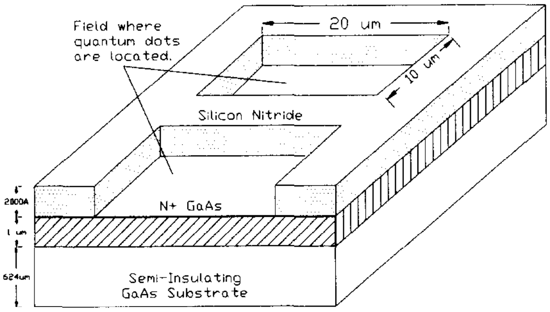

Figure 2: Sample layout geometry.

III. RESULTS

The sample described in this work consists of pairs of very closely spaced quantum dot diodes, whose construction has been described previously[4]. These structures were fabricated for the purpose of determining the coupling between closely-spaced, vertical, tunneling, quantum-dot devices. Understanding this coupling is important for the creation of an integrated circuit of extremely high functional density based on a cellular-automata architecture. The design spacing between the dots in each pair was varied from approximately 20 nm to about 100 nm. The design diameter of each quantum dot is nominally 150 nm. The entire sample is covered by a thick (0.2 μm) layer of silicon nitride except where 10 μm × 20 μm rectangular holes or windows have been etched in order to expose the GaAs surface, as shown in Fig. 2 (not to scale).

In each 10 μm × 20 μm rectangle there is a single pair of quantum dots. The site of the pair within the rectangular field is usually not precisely known; thus, finding it is somewhat like finding a "needle in a

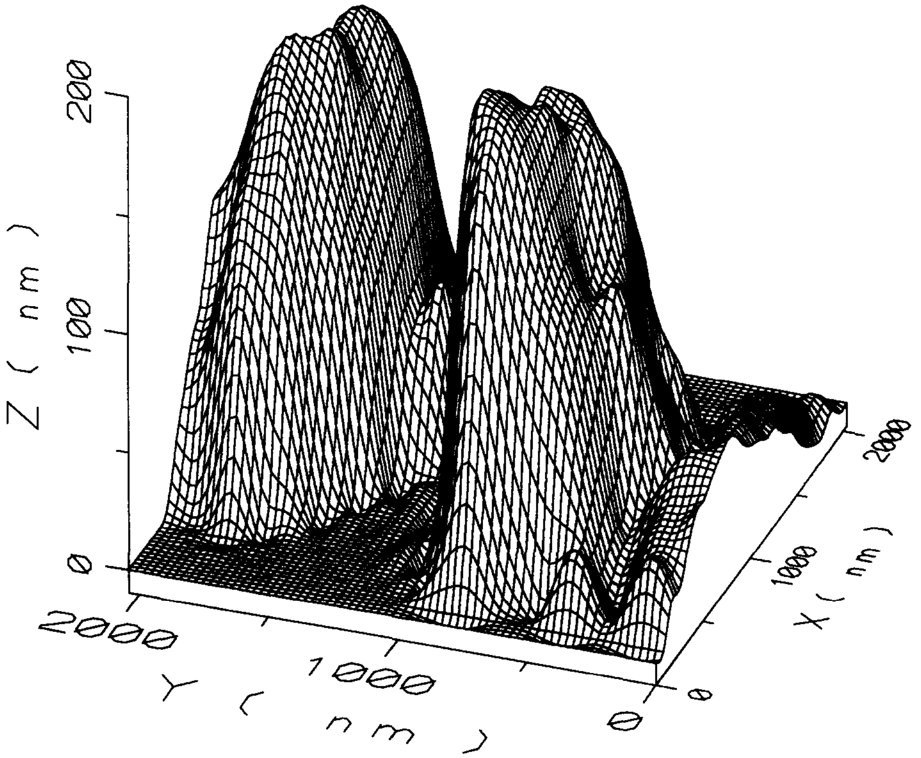

Figure 3: STM image of quantum dot pair.

haystack". Once coarse positioning has been achieved, the tube scanner is used to fine-scan and obtain an STM image. An image of two closely-spaced dots is shown in Fig. 3. Although it is not readily apparent in the oblique view shown in Fig. 3, line scans and plan views of the image show that each dot is approximately 200 nm in height and 150 nm in diameter with several tens of nanometers spacing between each dot edge. A zoomed-in view of the top of a single quantum dot is shown in Fig. 4. This compares favorably with the design parameters used for fabrication. The apparent merging of the two dots near the base shown in Fig. 3 might very well be due to the inability to fabricate two separate devices in such close proximity. However, difficulties in scanning the STM tip between two closely-spaced tall features could also account for the lack of resolution between the two dots.

IV. DISCUSSION

A serious difficulty in imaging man-made features, such as devices, using an STM is that conventional instruments are only capable of scanning very small areas at an unknown macroscopic location on the sample. In this work, the first high resolution images of quantum dots at identifiable locations on a macrscopic sample (integrated circuit) using a scanning tunneling microscope is reported. The development of a novel coarse approach system in conjunction with a STM permits the measurement of nanometer scale structures at desired locations relative to a reference point. Besides imaging, our technique also makes possible measurement of the electrical characteristics of individual quantum devices.

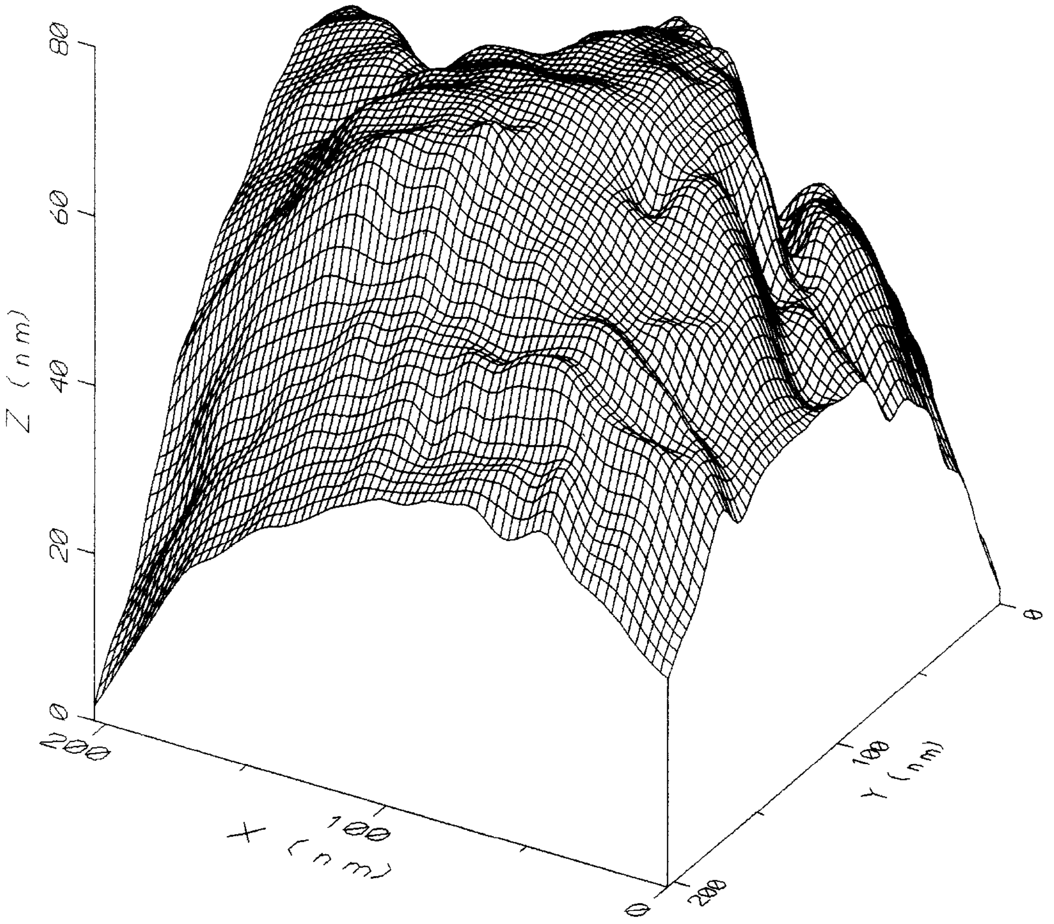

Figure 4: Top of a single quantum dot.

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