Available online at www.sciencedirect.com
ScienceDirect
Physica E 40 (2008) 1640–1641
PHYSICA E
www.elsevier.com/locate/physe

Lever arm of a metallic tip in scanning gate experiments

A.E. Gildemeister[a,*], T. Ihn[a], M. Sigrist[a], K. Ensslin[a], D.C. Driscoll[b], A.C. Gossard[b]

[a]*Solid State Physics Laboratory, ETH Zürich, 8093 Zürich, Switzerland*
[b]*Materials Department, University of California, Santa Barbara, CA 93106, USA*

Available online 17 October 2007

Abstract

We present a scanning gate experiment on the electrostatic interaction between a semiconductor quantum dot and the metallic tip of a scanning force microscope. With the help of a feedback mechanism we can map the lever arm of the tip, using the quantum dot in a given quantum state as a sensitive electrometer. Besides the geometrically expected shape at length scales of hundreds of nanometers, we observe fine structure on much shorter length scales.
© 2007 Elsevier B.V. All rights reserved.

PACS: 73.21.La; 73.23.Hk; 07.79.−v

Keywords: Scanning gate microscopy; Quantum dot; Lever arm

Experimental studies on electronic transport in quantum dots mostly employ macroscopic current and voltage measurements. A promising approach for measuring local properties of quantum dots is the scanning gate technique, where the sharp conducting tip of a scanning force microscope (SFM) is scanned as a movable gate over the surface of the sample. This technique has previously been used to manipulate single electrons in quantum dots in carbon nanotubes [1] and Ga[Al]As [2,3], where a quantum dot occupied by a single electron could be studied [4].

There are relatively few studies about an important factor common to all scanning gate experiments, namely the electrostatic potential that the tip induces in the sample. The importance of the tip potential for the interpretation of scanning gate measurements has been mentioned in some of the first studies [5] but only recently a technique was demonstrated allowing to determine it with high precision.

In Ref. [6] we used a quantum dot as a very sensitive potentiometer to study the tip-induced potential. We demonstrated how, with the help of a feedback mechanism, one can map the tip potential with high spatial and energetical resolution. Additionally, we showed how the tip's lever arm on the quantum dot can be mapped and used to better understand the properties of the tip potential. In these measurements we found fine structure which illustrates how the scanning gate technique may yield local information about the quantum dot. Here we show a measurement reproducing the main findings. The measurement conditions were identical as in Ref. [6], except that here an ac voltage of a lower frequency was applied to the tip.

We used a quantum dot prepared on a GaAs/AlGaAs heterostructure with a two-dimensional electron gas residing 34 nm below the surface. The quantum dot was patterned by local anodic oxidation of the GaAs surface at room temperature. Subsequently, we evaporated a thin Ti film on the sample surface and this film was again patterned by local anodic oxidation [7]. Directly above the quantum dot the Ti film was fully oxidized. Through this dielectric "window" the tip could interact with the dot.

We scanned the SFM tip at a constant height of about 200 nm over the sample surface. The dot was tuned into the Coulomb blockade regime, and we used a feedback mechanism to apply a voltage to a plunger gate such that one of the quantized energy levels of the dot always stayed in resonance with the chemical potential of the source and drain leads. The voltage on the plunger gate corresponds to the tip potential and with this technique we could ensure

*Corresponding author. Tel.: +41 44 633 3767.
E-mail addresses: gildemeister@phys.ethz.ch (A.E. Gildemeister), ihn@phys.ethz.ch (T. Ihn).

1386-9477/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2007.10.033

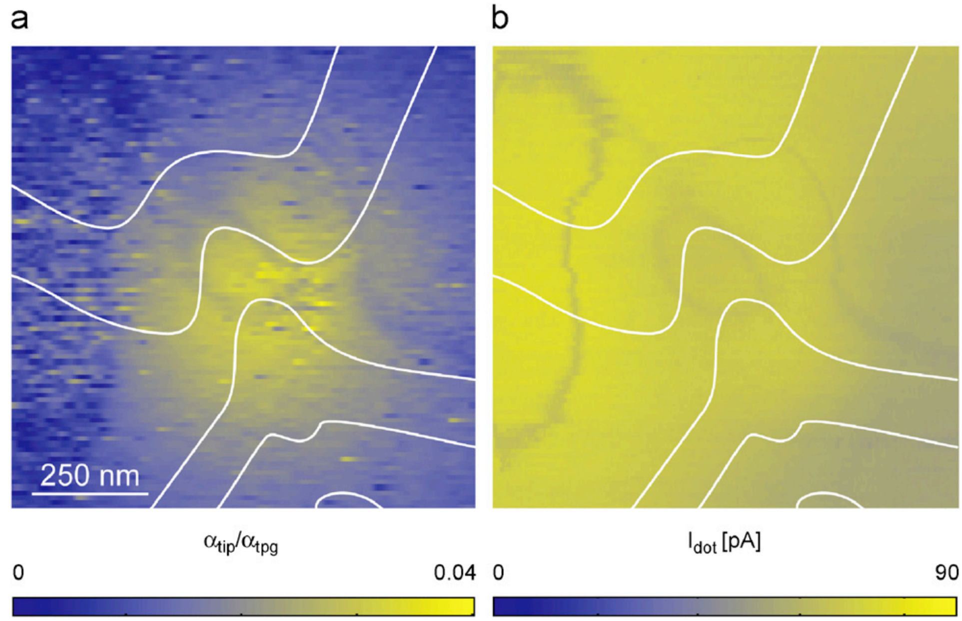

Fig. 1. (a) Relative lever arm of the scanned tip as a function of tip position. (b) Simultaneously measured current through the quantum dot. White lines indicate the contours of the oxide lines that define the quantum dot. The dot is formed at the center of the images.

that only one quantum state was used for detection. By applying an ac voltage to the tip at 1 Hz and measuring how strongly the feedback of the plunger gate reacted to this, we measured the lever arm of the tip.

The experiments were carried out in an SFM cooled by a dilution refrigerator [8]. The electronic temperature of the sample was about 190 mK. We used an electrochemically etched PtIr tip.

In Fig. 1(a) we show the tip's relative lever arm $\alpha_{tip}/\alpha_{tpg}$ measured with one quantum state of the dot. It is a good approximation to assume that the lever arm of the top plunger gate, α_{tpg}, is constant, and we measured $\alpha_{tpg} = 9.5\%$. The lever arm is highest when the tip is centered over the dot and it falls off as the tip is moved away from the dot, as one would intuitively expect. On top of this we find fine structure where the lever arm is suppressed on much shorter length scales. We can only speculate about the origin of this fine structure. It is correlated with a decrease of the current I_{dot} through the dot, shown in Fig. 1(b), which was measured simultaneously. We find that most lines of low $\alpha_{tip}/\alpha_{tpg}$ coincide with lines of low I_{dot}. The bandwidth of our feedback is decreased by a low dot current and possibly the low dot current could be the reason for a low measured lever arm. We think that the fine structure is not an artifact of the feedback mechanism for two reasons. In the present article we could show that it is reproducible for a fivefold smaller frequency compared to Ref. [6] and there we found different fine structure for different quantum states. Therefore, on the one hand, it would be possible that the fine structure is related to properties of the wave function. On the other hand, compared to a Fermi wave length of about 35 nm, the length scales of the fine structure, some 50 nm width and several hundreds of nanometers length, make an interpretation of the data in the sense of probability density mapping seem unlikely.

In conclusion, we have shown a measurement of the tip's lever arm performed using a quantum dot in a scanning gate experiment. The measurements of the tip's lever arm revealed fine structure both in the lever arm and the dot current similar to that found in Ref. [6]. We speculate that this fine structure may be characteristic for a quantum state.

References

[1] M.T. Woodside, P. McEuen, Science 296 (2002) 1098.
[2] A. Pioda, et al., Phys. Rev. Lett. 93 (2004) 216801.
[3] S. Kicin, et al., New J. Phys. 7 (2005) 185.
[4] P. Fallahi, et al., Nano Lett. 5 (2005) 223.
[5] G. Finkelstein, et al., Science 289 (2000) 90.
[6] A.E. Gildemeister, et al., Phys. Rev. B 75 (2007) 195338.
[7] M. Sigrist, et al., Appl. Phys. Lett. 85 (2004) 3558.
[8] A.E. Gildemeister, et al., Rev. Sci. Instrum. 78 (2007) 013704.