Observation of open quantum dot via low temperature scanning gate microscopy

N Aoki¹, A Burke², R Akis², D K Ferry², and Y Ochiai¹

¹ Graduate School of Advanced Integration Science, Chiba University
   1-33 Yayoi-cho, Image-ku, Chiba 263-8522, Japan
² Department of Electrical Engineering and Center for Solid State Electronics
   Research, Arizona State University, Tempe, AZ 85287-5706, USA

E-mail: n-aoki@faculty.chiba-u.jp

Abstract. Low temperature transport of a well-defined open-quantum dot has been studied via scanning gate microscopy (SGM). The open dot was fabricated on AlGaAs/GaAs heterostructure using trenches defined via electron beam lithography and a wet etching. The active size of the quantum cavity is approximately 1 μm × 1 μm. The SGM observation was performed at low temperature with a conductive piezolever, which is lifted up 50 nm above the surface with applied a negative voltage. During the scan of the tip, resistance across the dot is measured in a four-probe configuration and stored in a SPM controller synchronized with the position of the tip. The SGM response at zero-magnetic field shows a high resistance when the tip situates onto a line along the inlet and the outlet of the dot. The image could be understood as that the tip induced potential disturbs the current flow in the dot and it results in the increase of resistance. Such an image can be obtained even at more than 8 K, therefore this image would correspond to a classical transport. On the other hand, the image obtained at less than 2 K shows almost similar image as that observed at higher temperature. However, after subtracting the high temperature image as the background structure, which is achieved by a high pass filtering, conductance fluctuations are visualized in the low temperature image. These fluctuations would be attributed to a change of quantum interference condition as well as a manipulation of the wave-function confined in the open quantum dot.

1. Introduction

Scanning gate microscopy is one of scanning probe techniques and is a powerful toll to investigate a local transport property with a contrast to the topographic image. The technique is used for visualizing a quantum transport in a semiconductor quantum structure such as a quantum point contact (QPC) [1],[2] and quantum dot [3]. In this sense, an open quantum dot would be a good candidate structure for SGM observation because electron dynamics directly appear in the transport [4]. Such a transport, however, has been estimated by analyzing the results of resistance measurements, and by comparing with the computer simulation so far [5]. When a tip induced potential is brought into the dot, it would modulate the trajectory as well as the wavefunction scars and result in a change of the resistance. It could, therefore, be possible to visualize such phenomena directly in the real space if we apply the SGM to the structure. In this paper, we demonstrate a low-temperature SGM image obtained inside an open quantum dot and discuss what the image is visualizing.
2. Sample and experimental setup
The open quantum dot was fabricated on AlGaAs/GaAs heterostructure whose two-dimensional electron
gas (2DEG) was located at 60 nm below the surface. The structure was defined by 100-nm-deep trenches
fabricated by electron beam lithography and wet etching as shown in Fig. 1 (a). The mobility and the
mean free path of the 2DEG are $4.2 \times 10^4$ cm$^2$/Vs and 4.5 $\mu$m at 4 K, respectively. The lithographical size
of the dot and the observed area are 1.5 $\mu$m $\times$ 1.5 $\mu$m and 0.86 $\mu$m $\times$ 1.42 $\mu$m, respectively, as described in
Fig. 1 (a). The schematic setup of the SGM observation is shown in Fig. 1 (b). The observation was
performed at 300 mK with a conductive piezolever coated by Cr. The tip was lifted up 100 nm above the
surface and was scanned on the dot with applied a negative voltage (typically $-6$ V). During the SGM
observation, the resistance across the dot was measured by lock-in detector with a four-probe configuration
and the data was stored in a SPM controller synchronized with the tip position.

![Figure 1](image)

(a) Topographic image of the open quantum dot sample. The dot is defined by 100-nm-deep trenches. The lithographic size of the dot is 1.5 $\mu$m $\times$ 1.5 $\mu$m. An area surrounded by a broken line
indicates the area observed by SGM. The 2DEG situated at 60 nm below the surface is illustrated on the
cross section of the image. (b) Schematic drawings for the setting of the SGM observation. The 2DEG
underneath the tip is weakly depleted. Due to a surface depletion, the actual size of the dot would be much
smaller than the lithographic size. The resistance across the dot is measured by lock-in detector and is
stored in a SPM controller synchronized with the tip position.

3. Result and discussion
By applying a negative voltage to the tip ($V_{\text{tip}}$), SGM response begins to appear in the image. The
efficiency of the tip for obtaining a SGM image is different between at the QPC region and at the dot
region due to an existence of a saddle point potential at a QPC. It is very difficult to resolve both of
regions in one image due to a inadequate dynamic range of the lock-in detector. Therefore, the
observation is restricted as a rectangular area, shown by a broken line in Fig. 1 (a), where the tip does
not disturb the potential at the QPC. The image obtained with $V_{\text{tip}} = -3$ V is quite ambiguous however
it becomes clear at $V_{\text{tip}} = -6$ V as shown in Fig. 2(a). The resistance across the dot showed $\sim$2.8 k$\Omega$, when the tip situated far from the centre region of the dot. However, it increases when the tip comes
close to the centre and the resistance became maximum as $\sim$3.6 k$\Omega$. The brighter region corresponded
to a higher resistance appears along a line connecting between the inlet and the outlet of the dot. It
would be due to that most of current across the dot flows straight forward along this line at zero
magnetic field. Also, it indicates that the tip-induced potential obstructs the electron trajectory and it
results in the change of the resistance. If the tip maps out the change two as in two dimensionally, it would be shown as the SGM image. Therefore, the image changes by applying a perpendicular magnetic field because the trajectory becomes to deflect by the Lorenz force. This effect will be discussed elsewhere. Even at higher temperatures (8 K), the exterior of the image does not change. Because such a classical trajectory depends on the electron mean free path, \( l_0 \), the image does not change as long as the \( l_0 \) exceeds the size of the dot.

On the other hand, at a temperature lower than \( ~2 \) K, fluctuations of resistance appear superimposed to the image. Subtracting the back ground structure observed even at high temperature, which could be achieved by high pass filtering on the low temperature image, an image of fluctuations can be obtained as shown in Fig. 2(b). The amplitude is less than \(~10\%\) of the change of resistance in the SGM image. These fluctuations would come from quantum interference because such fine structures can be obtained only at low temperature. It indicates that such a quantum nature concerns not only to the \( l_0 \) but also to the phase coherence length (\( l_\phi \)). The tip potential changes the interference condition and this results in the fluctuations as observed inside a disordered QPC [6]. However, the relationship between the pattern of the fluctuations and the wave-function scaring should also be discussed because the tip potential could be able to manipulate it directory. Further analysis is necessary in the low temperature SGM images obtained with changing the magnetic field.

![Figure 2](image-url)

*Figure 2.* (a) SGM image observed at 0.3 K and zero magnetic field in an area shown in Fig. 1(a). The color scale indicates resistance when the tip situates at the point. (b) High pass filtered image of Fig. 2(a). These fluctuations can be observed only in images obtained at lower temperatures than \( ~2 \) K.

4. Summary

An open quantum dot has been observed via low temperature SGM. The SGM response shows high resistance around the center region of the dot along the line between the inlet and the outlet of the dot. Such a structure can be observed even at higher temperatures, therefore, the image would relate to a classical electron flow obstructed by the tip-induced potential. At lower temperatures than 2 K, fluctuations are observed on the SGM image. These fluctuations would be related to quantum interference in the dot and the variation of interference condition with a change of the tip position. Further experiments and analysis are necessary to clarify the meaning of the SGM images.

4. Acknowledgement

This work was supported by the Office of Naval Research and Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS, 19204030); N. Aoki was supported by the JSPS Post Doctoral Fellowships for Research Abroad 2004.
References

[1] Topinka M A, LeRoy B J, Shaw S E J, Heller E J, Westervelt R M, Maranowski K D, and Gossard A C 2000 Science 289 2323

[2] Aoki N, Cunha C R da, Akis R, Ferry D K, and Ochiai Y 2005 Appl. Phys. Lett. 87 223501

[3] Pioda A, Kicin S, Ihn T, Sigrist M, Fuhrer A, Ensslin K, Weichselbaum A, Ulloa S E, Reinwald M, and Wegscheider W 2004 Phys. Rev. Lett. 93 216801

[4] Ochiai Y, Widjaja A W, Sasaki N, Yamamoto K, Akis R, Ferry D K, Bird J P, Ishibashi K, Aoyagi Y, and Sugano T 1997 Phys. Rev. B 56 1073

[5] Bird J P, Akis R, Ferry D K, Vasileska D, Cooper J, Aoyagi Y, and Sugano T 1999 Phys. Rev. Lett. 82 4691

[6] Cunha C R da, Aoki N, Morimoto T, Akis R, Ferry D K, and Ochiai Y 2005 Appl. Phys. Lett. 89 242109