submitted to "ISANN" (Int.
Symp. on Nanooddevices and
Nanotechnology, Waikoloa,
Hawaii, December 02-07, 2007

Room Temperature Capacitance Imaging of Single Sub-Surface InAs Quantum Dots

J.Smoliner, W.Brezna, P.Klang, A.M.Andrews, G.Strasser
Institut für Festkörperelektronik, TU-Wien Floragasse 7, A-1040 Wien, Austria
E-mail: `juergen.smoliner@tuwien.ac.at`

Abstract. Scanning capacitance microscopy (SCM) is known to be a valuable tool for carrier mapping and profiling on nanoscale semiconductor samples. Certain applications, however, such as quantitative capacitance microscopy on InAs quantum dots, e.g. require low modulation frequencies and complete darkness, which are requirements completely incompatible with the current commercial SCM systems relying on a laser feedback system. For this reason, an intercepted feedback method was developed, which allows to switch off the laser temporarily while the feedback loop keeps running. As an application, images of sub surface InAs self assembled quantum dots were recorded. The InAs dots are clearly visible as bright areas in a contrast-rich capacitance landscape, which we attribute to local thickness variations of the InAs wetting layer in our sample.

1. Introduction

Since many years, atomic force microscopy (AFM) methods like scanning capacitance microscopy are known to be a valuable tool for carrier mapping and profiling on nanoscale silicon samples [1, 2, 3]. Thus, it was quite obvious to extend such studies to samples containing InAs quantum dots, especially because it was already known from quantum dot devices, that rich information on the electronic structure inside the dot can be gained [6, 7]. The realization of capacitance studies on single quantum dots by Atomic Force Microscopy (AFM) methods [4], however, is not straightforward: In the majority of commercial Atomic Force Microscopes, the motion of the tip is detected by monitoring the deflection of a laser beam shining onto the cantilever. A number of AFM based spectroscopic applications, however, such as scanning capacitance spectroscopy or photocurrent spectroscopy e.g., are severely disturbed by the intense stray light of the AFM laser. For this reason, we have developed an intercepted feedback procedure, where the AFM laser can be turned off up for several seconds while the AFM feedback loop keeps running. As an application, capacitance images of buried InAs quantum dots were recorded. Although the images were measured at room temperature, they reveal a feature rich potential landscape around the dots. In addition, spectroscopic data taken at on-dot and off-dot positions are clearly different and even show evidence of quantum states.

2. An intercepted feedback procedure for dark AFM measurements

If a light sensitive spectroscopic experiment has to be realized be realized on an AFM, there is no other way than freezing the feedback loop and switching the laser off while the measurement is running. Automating this procedure, however, is not straightforward because most commercial

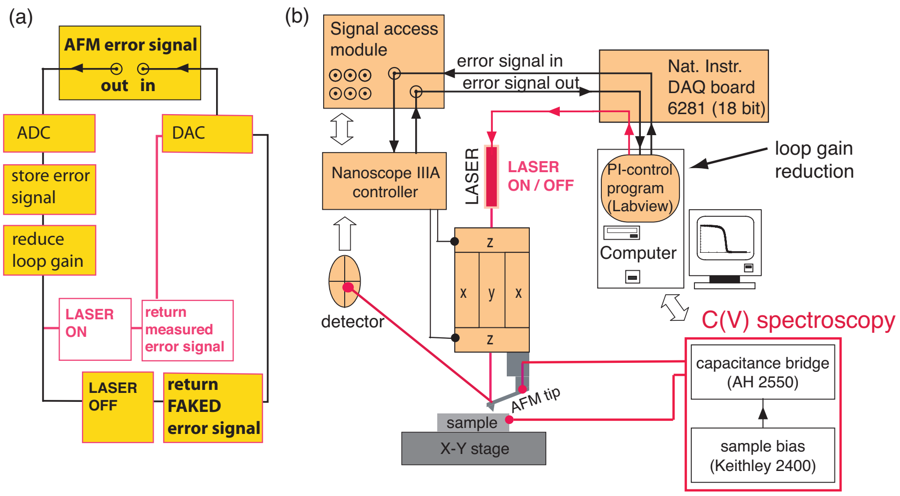

Figure 1. (a) Flow chart of the intercepted feedback procedure. (b) Block diagram of the experimental setup

AFMs do not allow to turn off the laser and freezing the feedback remotely. Moreover, the temperature drift of the scanning piezo in z-direction can be hundreds of nanometers within minutes and therefore does not allow to freeze the feedback loop over longer periods of time.

To avoid the problems related to a frozen feedback loop, we developed an intercepted feedback mode for our DI-3100, which is outlined in the flow chart and the block diagram of figure 1. The intercepted feedback mode works as follows: After the tip sample contact is established, the connection of the AFM error signal between the laser detector and the Nanoscope IIIA controller is opened using the DI-signal access module. From the signal access module, the error signal is read into a computer. As long as the laser is turned on, the error signal is stored by the computer software and then immediately sent back to the error signal input of the AFM. After the laser is turned off for a capacitance measurement, e.g., the buffered error signal is sent back from the computer to the AFM electronics in order to replace the missing detector signal. After the measurement has finished, the laser is switched on again, and the new detector signal replaces the buffered error signal. Note that this procedure is not restricted to the DI-3100 and was also installed it on a Molecular Imaging (now Agilent) Pico+ system for photocurrent spectroscopy. Before this feedback procedure can be used in practice, however, a number of technical details have to be considered: First, the AFM laser has to be controlled externally, which needs some modification of the AFM hardware. On the DI-3100, we located the mercury security switch inside the scanning head, which turns off the AFM laser when the scanning head is tilted for tip exchange. In series to the mercury switch, we installed an additional bipolar transistor switch, which allows to switch the laser on and off up to kHz frequencies. Accessing and feeding back the error signal for the DI-3100 is straightforward via the signal access module. The error signals were sampled using a NI-PCI-6281 data acquisition board, which offers 18 bit resolution for 16 analog input channels and 16 bit resolution for 2 analog output channels. The software for our intercepted feedback procedure was written in Labview and served several purposes : First, the software managed the input and output of the error signals in the intercepted feedback loop. Second, it controlled the spectroscopic measurement, and third, it was used to further reduce the proportional gain of the AFM-feedback loop. By reducing the proportional gain and the integral gain in the DI-3100 software (version v530r3sr3) to their minimal values of 0.0001 and 0.00007, respectively, data acquisition times in the order of 5 seconds could be achieved. For longer data acquisition times, however, the intercepted feedback loop starts to oscillate. A further reduction of the loop gain was therefore achieved through an additional PI-controller in our software. As we found, further reducing the proportional gain to a factor of 0.2 of the minimal gain of the DI-3100 software allowed a stable feedback behavior at data acquisition times of 20 sec. while the laser was switched off. Longer data acquisition times are possible too, but were not tested systematically. More details on this method can be found in [5] For capacitance spectroscopy and imaging, coaxial cables coming from an ultrahigh precision, low frequency (1kHz) capacitance bridge (Andeen Hagerling 2550A) were attached on both the sample and the AFM tip holder. For all measurements in this work, an excitation voltage of 0.375 V and an integration time of 12 sec. (averaging level 11) was used. This resulted in a total data acquisition time of 15 sec. per capacitance value including the time to adjust the feedback. In total this sums up to approximately 8 hours of data accquisition time for a capacitance image at a resolution of 40 x 40 pixel.

3. Capacitance imaging of sub-surface InAs quantum dots

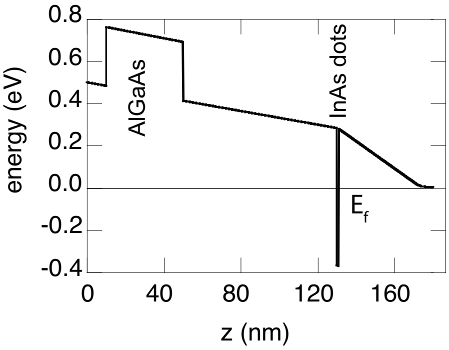

Figure 2. Conduction band profile of the InAs quantum dot sample.

The InAs quantum dot samples which we used for our capacitance studies were initially designed for photocurrent spectroscopy [8] , and had the following layer structure: on an n-doped (10^{18} cm^{-3}) back contact, a 40 nm i-GaAs layer was grown. On top, 1.55 ML of InAs were deposited at 500^0C followed by 80 nm of i-GaAs, a 40 nm thick $\mathrm{Al_{0.3}Ga_{0.7}As}$ blocking barrier, and a 10nm GaAs capping layer. The nominal dot density was in the order of 500μm^{-2}.

As tips, conductive diamond tips (N_A=1x10^{20} cm^{-3}) from Nanosensors were used. Here it is noteworthy, that "contact mode cantilevers" having a spring constant of 0.2 nN/nm could not be used because the achievable forces turned out to be too low to yield reliable capacitance data. The minimal force to obtain reproducible capacitance data was in the order of 1 μN which was achieved by using diamond coated "scanning spreading resistance cantilevers" with a high spring constant of 42 nN/nm. The physical origin for this behavior is probably found in the ambient conditions, where the scanning capacitance measurements were carried out. Under ambient conditions, all samples are usually covered with a thin film of water. Especially on semiconductors, one can expect an additional native oxide, too. Thus, the existence of a force threshold to penetrate these surface films with an AFM tip is not that surprising, the rather high amount of force in the order of 1 μN, however, is. To investigate this behavior in more detail, force dependent capacitance spectroscopy studies are currently performed on GaAs reference samples. The results will be presented in a forthcoming publication.

In figure 3 (a) a scanning capacitance image of sub surface quantum dots is shown, where the InAs dots are clearly visible as bright spots. The corresponding contrast mechanism is becomes obvious from figure 2: If the dots can be charged and de-charged by the modulation voltage of the capacitance bridge applied between tip and sample, the corresponding capacitance

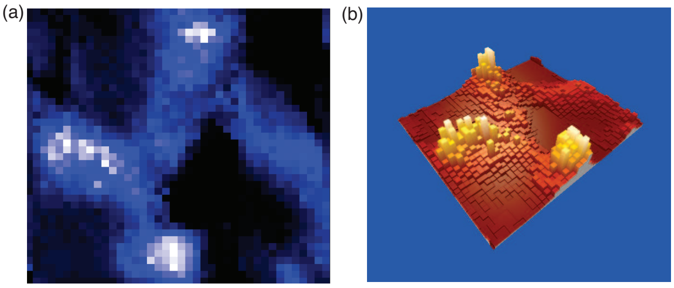

Figure 3. (a) Scanning capacitance image of sub surface quantum dots. Image area is 300nm x 300 nm. The sample bias was $V = -0.6V$. (b) same as (a) in 3D-view

will be dominated by the distance between the dots and the surface. In contrast to that, the wetting layer between the dots will not be charged, because the states in the wetting layer are located at much higher energies. As a consequence, the capacitance will be dominated by the distance between the highly doped collector layer and the surface, which is clearly larger than the distance between the dots and the surface. Thus, the dots appear as bright areas in the capacitance landscape.

Finally it has to be emphasized that the image contrast strongly depends on sample bias. On our present sample, best contrast was obtained at a bias of -0.6V. Here, a contrast rich capacitance landscape is also revealed in between the dots, which we attribute to local variations of the wetting layer. To explore the influence of sample bias and tip-force onto the image contrast, systematic capacitance measurements are currently in progress. As these measurements are extremely time consuming, the results will be presented in a forthcoming publication.

4. Summary

In summary, we have developed an intercepted feedback procedure for light sensitive spectroscopic measurements in atomic force microscopy. Through this procedure, the AFM laser can be turned off for several seconds while the AFM feedback loop keeps running. The method can be used for any light sensitive spectroscopic application and can in principle be realized on any AFM. As an application, images of sub surface InAs self assembled quantum dots were recorded on GaAs samples. Although measured at room temperature, the InAs dots were visible in the capacitance images as clear bright areas embedded in a contrast-rich capacitance landscape, which we attribute to local thickness variations of the InAs wetting layer in our sample.

Acknowledgments

This work was sponsored by FWF Austria, project SFB-025 TP08 and "Gesellschaft fuer Mikroelektronik (GMe)".

References

[1] V.V. Zavyalov, J.S. McMurray, C.C. Williams, Rev. Sci. Instr. 7, 158 (1999)
[2] R.Stephenson, P.DeWolf, T.Trenkler, T.Hantschel, T.Clarysse, P.Jansen, W.Wandervorst, Vac. Sci. Technol. B18, 555 (2000)
[3] P. De Wolf, R.Stephenson, T.Trenkler, T.Clarysse, T.Hantschel, W.Vandervorst, J.Vac. Sci. Technol. B18, 361 (2000)
[4] W.Brezna, T.Roch, G.Strasser, J.Smoliner, Semicond. Sci. Technol. 20, 903 (2005)
[5] J.Smoliner, W.Brezna, Rev. Sci. Instrum. 78, 106104 (2007)
[6] G. Medeiros-Ribeiro, F.G.Pikus, P.M.Petroff, A.L-Efros, Phys. Rev. B 55, 1568 (1997)
[7] R.J. Warburton, et al., Phys. Rev. B 58 (1998) 16221.
[8] G.Fasching, F.F.Schrey, W.Brezna, J.Smoliner, G.Strasser, K.Unterrainer, Phys. Stat.Sol. C2, 3114 (2005)