What can we learn about Quantum Wells with Atomic Force Microscopy?

Fall 2023 Phys 512 Term Project

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Atomic force microscopy (AFM) is a type of scanning probe microscopy (SPM) that uses a sharp tip placed on the end of a flexible cantilever to measure interactions between the tip and the sample [1]. One can determine the force exerted on the tip by the sample by measuring the cantilever's deflection. Thus, by scanning the surface, one can map out features of the sample.

To improve the signal to noise ratio, one can conduct frequency modulated AFM (FM-AFM) where the cantilever oscillates and the changes in the cantilever frequency are detected rather than the static deflection [2]. To understand the dynamics of the cantilever, one can assume that the tip of mass m is mounted on the end of the massless cantilever and treat it as a damped-driven harmonic oscillator. The dynamics of such a system are described by the equation

$$m\ddot{z} + \frac{m\omega_0}{Q}\dot{z} + m\omega_0^2 z = F_0 \cos\left(\omega_{\mathrm{d}} t\right) + F_{\mathrm{ts}}\left(z\right), \tag{1}$$

where z is the tip-sample separation, ω_0 is the resonant frequency of the cantilever, Q is the quality factor, F_0 is the amplitude of the applied driving force, ω_{d} is the driving frequency, and F_{ts} is the tip-sample interaction force.

AFM has been used to study defects and quantum dots, where so-called charging rings may be observed [3]. These charging rings appear when the energy level of the AFM tip aligns with an energy level of the quantum system. In this project, we want to study what parameters lead to this energy level alignment, and then find out what one can find out about the quantum system based on the characteristics of the charging ring. To do this, we will model a finite well and calculate the energy levels of the bound electrons. Then, we will investigate equation 1 via numerical methods to understand how the electrostatic forces these electrons exert on the AFM tip allow for the AFM to image charging rings. Once we understand what parameters lead to charging rings in AFM images we will make comparisons to real experimental data from the Grutter group.

References

[1] G. Binnig, C. F. Quate, and C. Gerber, *Atomic Force Microscope*, Phys. Rev. Lett. **56**, 930–933 (1986).

[2] T. R. Albrecht, P. Grütter, D. Horne, and D. Rugar, *Frequency modulation detection using high-Q cantilevers for enhanced force microscope sensitivity*, Journal of Applied Physics **69**, 668–673 (1991), `https://doi.org/10.1063/1.347347`.

[3] M. Cowie, T. J. Z. Stock, P. C. Constantinou, N. Curson, and P. Grütter, *Spatially resolved dielectric loss at the Si/SiO_2 interface* (2023), `2306.13648`.