X-ray Studies of Pb Quantum Size Effect (QSE) Islands Grown on Si(111)

E.H. Conrad,[1] R. Feng,[1] P.F. Miceli,[2] C. Kim[2]
[1]School of Physics, Georgia Institute of Technology, Atlanta, GA, U.S.A.
[2]Department of Physics and Astronomy, University of Missouri-Columbia, Columbia, MO, U.S.A.

Introduction

Epitaxial growth is a widely used technique to fabricate custom-made materials that do not exist in nature. Recent work has shown that below ~10 nm, the stability of a structure's size or shape is intimately related to the material's electronic properties. New structures grow with new topologies that are strongly influenced by electron confinement effects, as critical dimensions become comparable to the Fermi wavelength (λ_F) of electrons in the material [1-3]. The relationship between electron quantization and the geometry of the structure is known as quantum size effects (QSEs) [4].

An example of QSEs is Pb islands, grown on Si(111), that have uniform multistep height, flat tops, and steep edges [1-3]. In this system, the Pb islands are known to grow in bilayer increments. The bilayer period is a strong indication of QSE because the relationship between λ_F and d determines the Pb single step-height (i.e., $d = 3/4\lambda_F$). Since bilayer height increments add three nodes to the electron wave function, Pb layer thickness corresponding to $2d = 3\lambda_F/2$ is favored.

Important information is still missing for this comparison. For the Pb/Si(111) system, the thickness of the wetting layer formed between the Si and the Pb islands is a crucial piece of missing information. Different values have been given in the recent literature. The reason this information is so important is because the wetting layer thickness determines the quantum well height that confines the electrons. It is therefore the key to the quantum well states that form in the islands.

Methods and Materials

Experiments were carried out at the surface x-ray scattering chamber at MU-CAT beamline station 6-ID-C at the APS. The x-ray energy was set at 12.4 keV. Si(111) samples were prepared *in situ* by using standard techniques. Pb was deposited with an electron-beam evaporator from a moly crucible. Coverage was calibrated by measuring x-ray intensity oscillations (similar to reflection high-energy electron diffraction [RHEED] oscillations) for Pb deposition at 55K where Pb is known to grow in a layer-by-layer mode [5]. The deposition rate was fixed at 0.25 monolayer (ML)/min.

Results and Discussion

Figure 1 shows x-ray specular reflectivity data along the (11L) rod after 2.1 ML of Pb was deposited at a sample temperature of 150K. Even though only 2.1 ML of Pb was deposited, well-developed Pb(111) (L = 1.14) and Pb(222) (L = 2.27) Bragg peaks are clearly evident. The first indication of the island structure is the four interference fringes clearly seen between the Pb(111) and Pb(222) Bragg peaks, indicating a film with a thickness corresponding to six Pb layers. Previous low-energy electron diffraction (LEED) measurements indicated that Pb columns grown at this temperature are five Pb layers high [3]. Since LEED measures island heights by looking at interference between the top of the island and the nominal surface, the measurements are insensitive to the Pb wetting layer between the islands and the Si substrate. These x-ray measurements clearly indicate a 1-ML wetting layer thickness (i.e., 5-ML-high islands plus a 1-ML wetting layer).

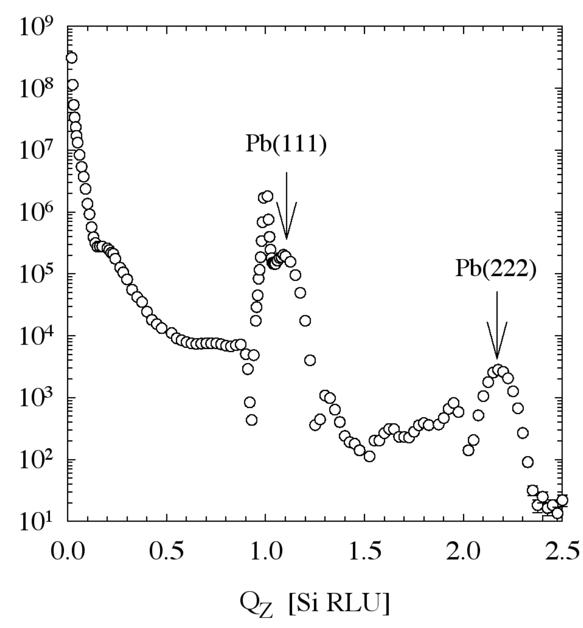

FIG. 1. Measured x-ray reflectivity from 2.1 ML of Pb deposited on Si(111) at a temperature of 150K. Arrows mark the position of the Pb(111) and Pb(222) Bragg peak.

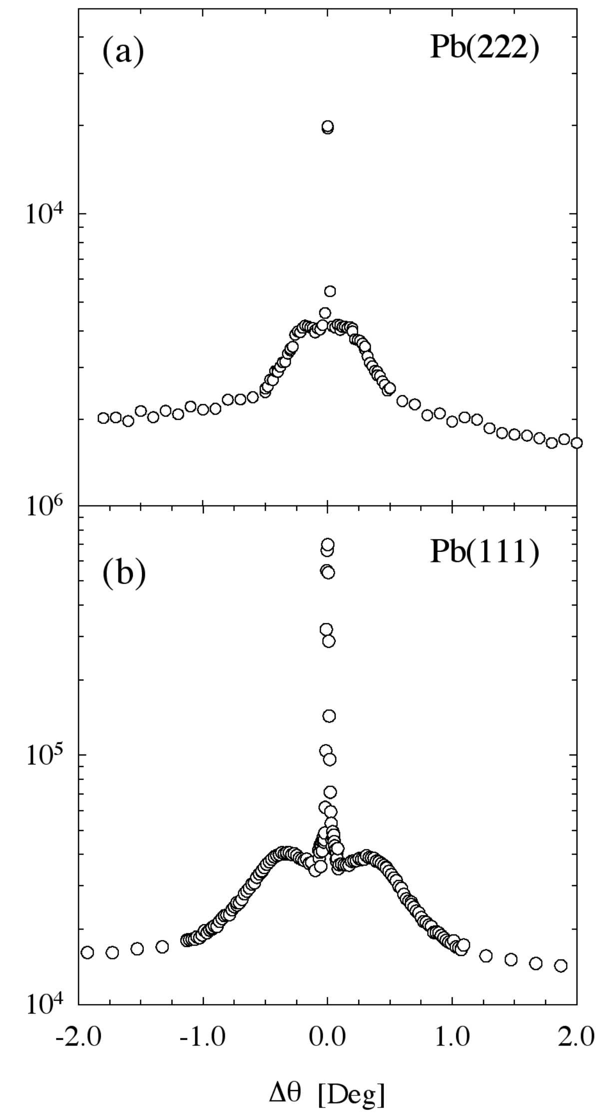

FIG. 2. Transverse scans across the (a) Pb(222) and (b) Pb(111) Bragg peaks showing lobe structure corresponding to six-layer Pb islands with a mean separation of 40 nm. Data are for 2.1 ML of Pb deposited on Si(111) at a temperature of 150K.

We have also measured transverse scans at the Pb(111) and Pb(222) Bragg points. Figure 2 shows that well-developed diffuse tails are present. Note that the width of the diffuse tails at (222) is half the width of the tails at (111), indicating that the tails are not from mosaic scattering but are instead from coherent scattering [6]. The diffuse tails have well-developed satellite peaks symmetrically located around the Bragg point. The satellite peaks are due to scattering from Pb islands on top of a Pb wetting layer with an imposed Si(111) 7×7 lattice constant. The satellite peak positions are a direct measurement of the mean island spacing (40 nm in these experiments).

Acknowledgments

Use of the APS was supported by the U.S. Department of Energy (DOE), Office of Science, Office of Basic Energy Science (BES), under Contract No. W-31-109-ENG-38. The MU-CAT sector at the APS is supported by DOE BES through Ames Laboratory under Contract No W-7405-ENG-82.

References

[1] L. Gavioli, K.R. Kimberlin, M.C. Tringides, J.F. Wendelken, and Z. Zhang, Phys. Rev. Lett. **82**, 129 (1999).
[2] W.B. Su, S.H. Chang, W.B. Jian, C.S. Chang, L.J. Chen, and T.T. Tsong, Phys. Rev. Lett. **86**, 5116 (2001).
[3] K. Budde, E. Abram, V. Yeh, and M.C. Tringides, Phys. Rev. B Rapid Communications **61**, 10602-10605 (15 April 2000).
[4] M. Jalochowski, M. Hoffmann, and E. Bauer, Phys. Rev. B **51**, 7231 (1995).
[5] D. Schmicker, T. Hibna, K.A. Edwards, P.B. Howest, J.E. MacDonald, M.A. James, M. Breeman, and G.T. Barkema, *Surf. Sci.* **424**, 169 (1999).
[6] P.F. Miceli and C.J. Palmstrom, Phys. Rev. B **51**, 5506 (1995).