Grazing incidence fast atom diffraction – a new tool for semiconductor surface analysis of semiconductors under epitaxial growth conditions

The telecommunications revolution has its roots in the development of epitaxial growth techniques in the 1970s. High speed electronic devices and high performance lasers rely on the ability to accurately grow single crystal, high purity, semiconductor thin films. The current degree of control over thin film growth and crystal quality has been reached thanks to the ability to monitor the surface in-situ during growth using reflection high energy electron diffraction (RHEED). An alternative to this, based on diffraction of fast atoms from the surface has recently been developed by scientists at the INSP (Team Growth and properties of hybrid thin film systems) and ISMO (Institut des Sciences Moléculaires d’Orsay). Grazing Incidence Fast Atom Diffraction (GIFAD) can be used both to monitor molecular beam epitaxial layer-by-layer growth in real-time and to experimentally verify ab-initio calculations of surface reconstructions and atom-surface interaction potentials. Similar in its ease-of-use to RHEED; GIFAD has a much greater surface sensitivity, with the potential to aid the research and development of next-generation devices.

Grazing Incidence Fast Atom Diffraction (GIFAD) combines the advantages of RHEED, such as compatibility with molecular beam epitaxy (MBE) as shown in Fig 1(a), with the extreme surface sensitivity of thermal atom scattering. In GIFAD, the incidence angle of a neutral He atom beam, (energy < 1 keV) is less than ~2°. Due to this shallow angle, the energy normal to the surface is sufficiently low (< 500 meV) ensuring that the atoms do not penetrate or damage the surface, but instead scatter elastically from the surface with a minimum probe atom-surface separation of several Angstroms. The rapid motion of the probe He atoms is unaffected by the interaction between the He atoms and the surface, with the result that the interaction potential between the fast He atoms and the surface is averaged along the direction of the beam. Along high symmetry (low-index) directions of the surface reconstruction, the surface therefore appears as a series of parallel channels to the probe atoms. Thus, to a first approximation, fast atom diffraction from a surface can simply be considered as diffraction of low energy atoms from a 2-D diffraction grating. From the diffraction pattern, shown in figure 1(b), both the periodicity of the surface reconstruction, and the shape (or corrugation) of the interaction potential between the helium atoms and the surface can be extracted. By changing the incidence angle, details of this interaction potential can be probed.
During layer-by-layer growth the surface roughness varies in an oscillatory manner, as islands nucleate, grow and then coalesce to form a complete layer. This variation in surface roughness can be easily followed using GIFAD (see movie for changes in GIFAD intensity during GaAs growth) since step up (down) edges lead to super- (sub-) specular scattering of the incident He atoms away from the Laue circle. Unlike RHEED oscillations, where the electrons penetrate the surface and undergo multiple scattering events, in GIFAD the probe atoms typically only interact with the surface at a single impact point. The result is that the phase and magnitude of GIFAD intensity oscillations during growth do not depend on the scattering geometry. In addition, in GIFAD all the diffraction orders oscillate in phase, so that the intensity over the entire Laue circle can be used to monitor the change in the surface reflectivity. This makes GIFAD a very robust technique to measure changes in surface roughness during growth, even when a change in surface reconstruction occurs during growth [1].

GIFAD also provides the possibility to rapidly test models of surface reconstructions and to quantitatively test theoretical calculations of atom-surface interaction potentials [2]. Figure 2 (a) shows that a large number of diffraction orders can be resolved from the Despite the GaAs surface being held at 530 °C, under an incident As4 flux. This demonstrates the robustness of fast atom diffraction under optimal conditions of semiconductor growth.

The chain-like structure seen in the diffraction charts can be rapidly correlated to gross features of the surface corrugation by a semi-classical ray-tracing analysis [fig 2(b)]. Path interference between atoms scattered from the turning points 1,1’ and 2,2’ of the surface corrugation profile, gives rise to the rapid intensity modulation of each diffraction order with perpendicular beam energy; interference between atoms scattered from points 1,1’ and 3, or 2,2’ and 4 gives rise to the slower intensity modulation, resulting in the chain motif experimentally observed.

By carrying out a full quantum scattering analysis [figure 2(c)], both the ab-initio calculated atom-surface interaction potential and surface reconstruction can be verified, showing good agreement with experimental data for atom perpendicular energies > 30 meV. At lower energies, comparison between experimental and quantum scattering calculations highlighted the inaccuracy in current ab-initio methods to properly account for the van-der-Waals attraction between probe atom and surface, and allowed the discrepancy to be quantified [2].
In summary, we have recently demonstrated that Grazing Incidence Fast Atom Diffraction is fully compatible with conditions used for conventional molecular beam epitaxial growth of semiconductors, and allows both dynamic measurements of the growth process and high resolution static measurements of surface reconstructions to be made. This is a useful addition to the toolbox both for surface and epitaxial growth scientists, opening up an avenue to test theoretical models of growth and atom-surface interactions.

**References**

[1] "Dynamic grazing incidence fast atom diffraction during molecular beam epitaxial growth of GaAs"  

[2] "Combined experimental and theoretical study of fast atom diffraction on the β2 (2 × 4) reconstructed GaAs(001) surface"  

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