Atomic-resolution electron microscopy and spectroscopy can now determine composition and electronic structure not only of individual nanostructures, but also of individual defects, interfaces or atomic columns inside those nanostructures\(^1,2\) (Fig. 1). The sensitivity and resolution extends to the imaging of single dopant atoms or vacancies buried inside their natural environments, allowing us to study the early stages of precipitate nucleation and identify the clusters responsible for electrical deactivation in integrated circuits\(^1,3\). In fact, the smallest feature in a modern transistor, the gate oxide, is already little more than an interfacial layer just over 5 atoms thick, and the fundamental limits to device scaling are set by the measured electronic structure –determined by atomic-scale electron spectroscopy\(^4\) (Fig. 2).

Modern developments in electron microscopy and spectroscopy have place within reach the ultimate goal of knowing the location, chemical, optical and electronic properties of every atom in a nanostructure. Since the early 1990’s it has been possible to map chemical and bonding information at the atomic scale using a scanning transmission electron microscope (STEM)\(^5,7\). Here a high energy electron beam is focused down to an atomic sized probe. The passage of a beam of swift electrons through a thin film induces dipole transitions, exciting core electrons to states above the Fermi level. Electron energy loss spectroscopy (EELS) of the transmitted beam reveals detailed information about the local electronic structure, in particular the conduction band density of states partitioned by site, angular momentum, and atomic species. With improvements in detector efficiency it has become possible to apply this spectroscopy to the study of grain boundaries and buried interfaces using 2-5 Å wide probes\(^8,9\).

More recently, we have succeeded in obtaining the first images of single impurity atoms inside a crystal\(^3\), a task requiring extraordinarily smooth samples and a quiet measuring environment, even with a state-of-the-art electron microscope. These proved to be key enablers for work on dopant deactivation, device scaling, and understanding the chemistry of oxide heterostructures\(^1,4\). By combining these methods with two recent developments, a high energy resolution spectrometer on a monochromated electron microscope column, and aberration correctors\(^10\), we will be in a position to perform subnanometer (and possibly subangstrom) energy loss measurements on a scale relevant to the optical and electronic properties of nanoparticles and interfaces encased in their natural environments.

**Fig.1.** A scanning transmission electron microscope image of a growing Er cluster buried in silicon carbide\(^7\). The segregation of erbium to defects leads to the formation of optically inactive clusters which are too small to detect by conventional microscopy. Core Loss spectroscopy at 1eV resolution identifies the Er atoms in the cluster. At the 0.1 eV energy resolution available on next-generation prototypes, valence EELS may be able to identify which of the Er atoms or clusters are optically active.
Breakthroughs in instrumentation and algorithms have dramatically changed the field of electron microscopy, opening new areas from the imaging and spectroscopy of individual dopant atoms and clusters buried inside commercial semiconductor nanodevices to the three-dimensional tomography of nanoparticles, viruses, and biological structures and the in-situ observations of nanomechanical deformations and electrodeposition. Early results in sub-angstrom resolution and millivolt spectroscopy are now being applied to nanoscience problems, and the national initiatives in aberration-corrected instruments (such as the TEAM project) should make such facilities available to the wider community, and enable new in-situ experiments. Areas where electron microscopy provides unique tools for the study of nanoscience include, amongst others:

- Three-dimensional Electron tomography for nanoparticles, semiconductor devices and biological materials, often at subnanometer resolution
- Electron holography for mapping nm-scale magnetic and electric field in structures as diverse as magnetic bacteria and doped semiconductors
- Imaging of single atoms, clusters and vacancies buried inside materials
- Electron spectroscopy at high spatial and energy resolution for sub-nm chemical and optical properties
- Smaller than an atom: Aberration corrected microscopes for imaging with sub-angstrom resolution.
- Imaging individual molecules and defects in biomaterials
- In-situ microscopy using environmental cells of deformation and growth (even in liquids)

![Electronic structure of a nanotransistor](image)

**FIG. 2.** Electronic structure of a nanotransistor: (a) The oxygen profile measured by EELS in a STEM from a 1 nm gate oxide. The interfacial states changes the shape of the O-K edge, which is used to map bonding changes across the oxide. (b) The corresponding ADF-STEM image, where the circles indicate the positions at which the O-K edge spectra (panel c) were recorded.