the design of future plasmon-enhanced data-processing and transport capabilities[10,11]. The high frequency of light enables significantly higher operating speeds and the use of components that are naturally more compact compared with the RF regime. The widespread adaptation of circuit models in the optical regime could accelerate the pace of technological advances in virtually any nanoscale optics application. As such, it may also have an impact on the development of the recently emerging metamaterials[12], consisting of large numbers of deep subwavelength building blocks. Such materials may well provide the ultimate control over the flow of light in time and space, enabling new photonic devices we have not even started dreaming about.

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LASER-GENERATED PLASMAS

Probing plasma dynamics

Researchers in Germany have shown that an ultrafast electron beam can be used to probe the dynamics of laser-generated plasmas with picosecond resolution.

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The field of atomic and molecular physics shares many features with plasma physics. Both deal with electrons and ions, as well as electric and magnetic fields. The major difference is one of focus. For atoms and molecules, the most important electrons are bound, and in this confined environment quantum effects play a major role. For plasma physics, free electrons are the primary focus and as these electrons exist in a continuum, quantum effects are less important.

In the boundary between these two regimes of physics lies the exciting area of optical-field ionized plasmas — the subject of the paper on p315 of this issue by Martin Centurion, Peter Reckenthaeler and colleagues in Germany[1]. The authors use a high-intensity femtosecond 800-nm light pulse to transform a nitrogen gas into a plasma, and then demonstrate a new method for imaging its electric-field distribution with picosecond resolution as the plasma expands.

With optical-field ionization, atoms or molecules are ionized by a laser field, perhaps augmented by plasma fields[2], and the newly freed electrons respond nearly classically to the force exerted by the electric field[3]. The topic is important because the initial conditions of the plasma (for example, its ionization state[4], electron temperature[3], ion temperature and internal magnetic fields[5]) are established by atomic and laser parameters. As a result, extremely unusual plasmas, far from equilibrium, can be created.

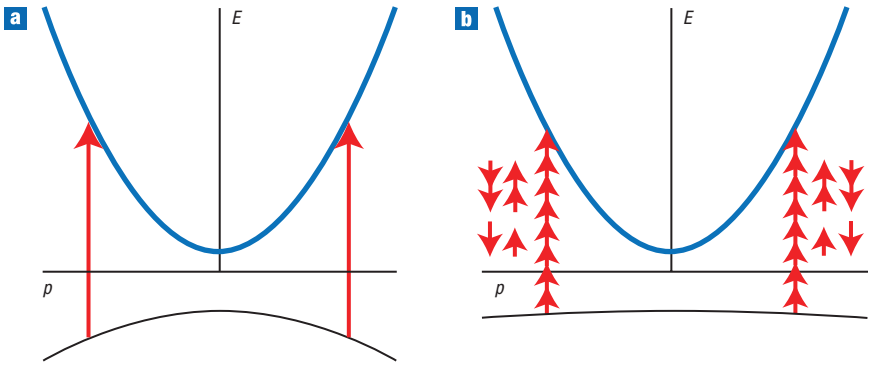

Figure 1 A solid-state analogy of an optical-field ionized plasma. **a**, The valence (black) and conduction (blue) band structure of a direct bandgap semiconductor. Photoexcitation (represented by the red arrows) transfers the electron population from the valence band to the conduction band, creating a non-equilibrium electron–hole plasma. The band curvature determines the effective mass of the electrons and holes. **b**, The electron (blue) and ion (black) dispersion curves of an atom. Multiphoton excitation (usually approximated by tunnelling but represented here by one of many complex multiphoton pathways) transfers electrons from the atom to the continuum, creating a non-equilibrium electron–ion plasma. The dispersion curves are determined by the electron and ion masses.

An analogy with solid-state physics is particularly helpful when considering how to analyse the dynamics of such plasmas. In a typical ultrafast solid-state experiment (Fig. 1a) a single photon can transfer an electron from the valence band (illustrated in black) to the conduction band (illustrated in blue). The energy and momentum of the electrons and holes are determined by the energy of the exciting photon. The dynamics of such a system can be analysed by using a probe pulse (not shown) to measure the electron (or hole) relaxation back to equilibrium.

In optical-field ionized plasmas (Fig. 1b), many photons transfer an electron from an atom or molecule (the dispersion relation for the ion is represented in black) to the continuum (the electron dispersion is illustrated in blue). The energy and momentum of the electron and ion are

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determined by the interplay of the many multiphoton pathways (tunnelling). Only one of many contributing multiphoton pathways is illustrated in the figure. These plasmas are a natural laboratory for studying non-equilibrium plasma responses.

Pump–probe spectroscopy is far less common in optical-field ionized plasmas than in molecular science or in solid-state physics, where it is now a routine and useful analysis technique. The innovation of Centurion *et al.* is to use picosecond electron deflectometry to analyse their plasmas. The paper describes a pump–probe experiment in which the probe pulse is a 20-keV electron beam of picosecond duration.

Picosecond or femtosecond electron beams, synchronized to a femtosecond light pulse, are just beginning to be used as probe pulses in molecular[6] and solid-state[7] physics. There, the most important electric fields are concentrated near the ion cores of each atomic constituent. The scattered electrons provide information about these fields. In ordered materials, each ion centre contributes coherently, creating a diffraction pattern[6,7]. In plasmas the important field structures are usually on a larger scale, reflecting the fact that the important electrons lie in or near the continuum.

Centurion *et al.* show that electron beams can be an effective probe of internal plasma fields — especially for fields that extend over a relatively large spatial region. In their field-ionized plasmas they follow the dynamics of the electric fields created when the hottest electrons escape the plasma. These space-charge fields confine the lower-energy electrons, and the researchers observe the dynamics of these electrons as the plasma expands.

In their paper, the research team demonstrate a new measurement method. It is a major advance because optical-field ionized plasmas have important applications. For example, it is possible to create transient plasmas with population inversions in the extreme-UV spectral region. This offers a route to X-ray lasers[8] that can be improved with better diagnostics.

Ultrafast electron bunches, synchronized to femtosecond pulses are a relatively new diagnostic tool for atomic, molecular and solid-state science. The technical hurdles to the improvement of the time resolution of such electron bunches are similar to those encountered in the early days of ultrafast optics. Laser researchers overcame the obstacles to the generation of shorter pulses by developing methods of dispersion control, and now scientists are applying analogous methods of chirp compensation in electron accelerators[9]. As the technology for creating ultrashort electron bursts improves, they will become standard diagnostics in the ultrafast experiments of the future, not only for laser-produced plasmas but in many areas of science.

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MICROSCOPY

Polarized high-resolution imaging

By making use of polarization control, researchers have achieved a record 100-nm resolution when imaging buried transistors in an integrated circuit.

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The spatial resolution of a microscope is a key performance criterion in many scientific and industrial applications. At present, only the most advanced electron and scanning-probe microscopes can resolve the atomic-scale features of modern integrated circuits. However, the non-destructive imaging of buried transistors, which is necessary for integrated-circuit analysis, requires subsurface optical microscopy. The challenge is that the imaging resolution must be continually improved to match the ever shrinking size of transistors. A focused light beam from a microscope is often shone onto the circuit to induce carrier generation in the transistor silicon and the resolution of the measurement is determined by the size of the focal spot. Keith Serrels and his colleagues at Heriot-Watt University in the UK have now performed this type of experiment with a record 100-nm resolution, as described on page 311 of this issue[1].

The key challenges to improving the resolution of optical microscopy of buried transistors stem primarily from the materials involved. The silicon substrate is the only practical optical path to reach the transistors, because the metal interconnects fabricated on top of the transistors are opaque. The focusing of light is ultimately limited by diffraction to a minimum spot size that is proportional to the wavelength. As the silicon substrate is only transparent at infrared wavelengths, greater than 1 μm, this limits the minimum size of the focused spot. However, nonlinear absorption processes, such as multiphoton absorption, can overcome the resolution limit imposed by the minimum spot size. In one- and two-photon absorption processes, the absorption probability is proportional to the optical intensity and its square, respectively. Thus, changing from a one to a two-photon absorption process improves the lateral resolution by a factor of $\sqrt{2}$, when the focused spot is gaussian. In silicon, the resolution improvement is reduced, because wavelengths of greater than 1.2 μm are necessary for two-photon absorption to dominate[2].

The angular-spectrum representation[3] of an optical beam defines the amplitude, phase and polarization of light,

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