ULTRAFAST PHOTONICS

On-chip tunnel management

Speed is of the essence when it comes to signal processing, but electronic switching times have reached a limit. Optically controlled tunnel currents across a nanoscale plasmonic gap could considerably accelerate future nanoelectronic devices.

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Charge-carrier control in solids lies at the heart of electronic signal processing and today's information technologies. Conventional electronic circuits operate with voltages that switch electric fields at gigahertz rates. While these rates are truly impressive, there is always appetite for higher speeds. The oscillating electric field of a light wave makes for an ambitious target: it changes direction five to six orders of magnitude faster than current electronics, switching the 'voltage' at petahertz rates (for near-infrared light). What's more, modern light-generation technology can flexibly sculpt individual light oscillations in the infrared and visible spectral range. One cannot help but dream of lightwave electronics at petahertz rates[1,2], where charge flow and information processing would use individual oscillations of light rather than conventional voltages. However, major fundamental and technological challenges have to be met to make this dream come true: from deeply understanding the basic interaction of intense light fields with solids to building electronic circuits that can be operated with light. Markus Ludwig and colleagues have now built on previous work[3–5] to make big strides in meeting both challenges[6].

Ludwig and colleagues succeeded in controlling and 'filming' — albeit indirectly — the electron transport across the gap with sub-femtosecond temporal resolution. They also made an important technological advance by demonstrating a plasmonic nano-circuit driven by an optical pulse. Crucially, the highly nonlinear optical process that activated the nano-plasmonic circuit was driven with pulse energies of only about 20 pJ. The bow-tie configuration, with a gap just a few nanometres across, concentrated this energy into a tiny volume, and the hundred-fold plasmonic enhancement of the electric field provided the voltage necessary to force electrons to tunnel across the nano-gap, from one tip of the bow-tie to the other (Fig. 1). In contrast to enhanced fields generated by a single nanoparticle, the electric field in a bow-tie gap is spatially quite uniform, which is important for the nano-circuit performance.

The current in the nano-circuit was triggered by a light pulse that contained only a single strong oscillation of the electric field. With such a single-cycle pulse, the phase of the field oscillation under the pulse envelope — the carrier–envelope phase — controls the direction of the electric current. For a linear optical response, the carrier–envelope phase does not matter, but any nonlinear response is acutely sensitive to the maximum strength of the electric field. For such processes, the carrier–envelope phase matters a great deal: it determines the direction in which the maximum electric field of the single-cycle pulse would point, and thus controls the direction of the electron current.

In the simplest picture, the current should be zero when the field under the envelope is sine-like, with two identical field maxima pointing in the opposite direction. A cosine-like pulse, with the clear single maximum of the electric field, should trigger a single burst of current, determining its direction. This simple picture turns out to be not too far from reality, as long as one looks not at the electric field in the free space but at the electric field inside the gap. The deviations arose from the plasmonic response, which modified the total field inside the gap and changed its effective carrier–envelope phase. There was also memory in the system because of the electrons already injected into the gap by the first peak of the electric field: the second field peak could help or hinder these electrons during their journey. At the same time, electrons generated by the second peak were left to travel across the gap without any further disturbance. These details notwithstanding, smooth control over the carrier–envelope phase allowed Ludwig and colleagues to fully switch the direction of the current.

To resolve the electron transport in time, the authors used a sequence of two identical pulses with a controlled time delay between them, measuring the resulting current as a function of the delay time and the carrier–envelope phase. In effect, they looked at the highly nonlinear version of the interferometric autocorrelation. In general, interferometric autocorrelation does not readily offer reliable temporal reconstruction. However, here the situation was different. Firstly, the current was a highly nonlinear function of the incident field. Secondly — and more importantly — the measurement was two-dimensional: it depends not only on the delay time, but also on the carrier–envelope phase. Whether there is a general algorithm that can uniquely reconstruct the temporal profile of the current from such a two-dimensional measurement is not yet clear. Fortunately, it appears that such reconstruction is also not necessary, as excellent agreement between theoretical and experimental two-dimensional maps of the current provided the desired sub-femtosecond view into the dynamics of electron transport.

Looking further afield, such experiments are rapidly changing the face of attosecond

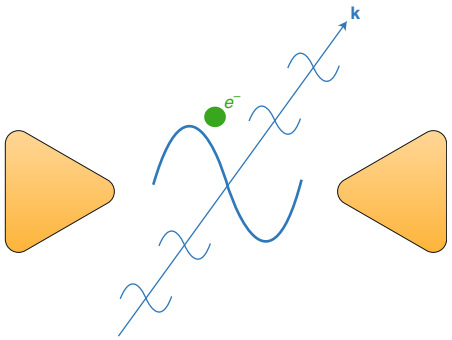

Fig. 1 | A single-cycle light pulse (blue curves) forces electrons (green dot) to tunnel through the gap in a bow-tie plasmonic device. Control over the phase of electric field oscillation in the pulse determines the direction of tunnelling. The bow tie acts as an antenna enhancing the local electric field by two orders of magnitude, enabling the generation of tunnelling current at picojoule pulse energies. **k**, pulse propagation direction.

science. Attosecond control of the instantaneous electric fields allows sub-femtosecond control of field-driven processes in solids. Controlling the field-driven response in nanoscale solid-state targets with picojoule energies is a welcome shift that could make photo-switches, photo-cathodes and photo-detectors operating at petahertz rates possible. This may open opportunities for combining Ångstrom-scale spatial resolution of scanning tunnelling microscopy with sub-femtosecond temporal resolution. In principle, ultrafast electron currents can also be made spin polarized — a feat that has already been accomplished in optical tunnelling from atoms[7,8]. This would allow the interrogation of magnetic materials with femtosecond temporal and nanoscale spatial resolution. On-chip attosecond science with infrared light sources might have a bright future. ❐

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Published online: 6 March 2020
https://doi.org/10.1038/s41567-020-0800-5

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