Tailoring Optical Near Fields for Achieving Laser-Field-Driven Ultrafast Electronic Devices

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Advances in phase-stabilized pulsed lasers have opened an avenue to field-induced nonlinear optical phenomena, such as field ionization and high harmonic generation. The scope of these strong-field phenomena has been mainly focused on gaseous media, and is extended to solids more recently, and possibilities to steer electrons by the optical fields have been proposed. For example, electron emission from a metal nano tip is shown to be sensitive to the waveform of a few-cycle laser pulse, which could open a way to "petahertz" electronics operating at optical frequencies.

Electronic devices can be decomposed into elementary units, such as a cathode and an anode in a diode; an emitter, a base and a collector in a bipolar transistor. In conventional semiconductor electronics, properties of the units are controlled by the material's properties such as doping concentrations, and the geometries of the materials. In a similar way, the metal nano tips are expected to work as elementary units for electronic devices using laser-field-driven electrons as carriers. However, one difficulty arises when such a tip-based electronic device is under a laser focus: the laser spot size is much larger than the required length scale of the structures, and so one cannot selectively create carriers at a nano tip. Namely, the traveling distance of an electron with an energy of ~ 1 eV is typically ~ 0.6 nm within a single optical cycle (~ 1 fs). Therefore, the electric channels should be formed within these short length scales for electronic devices operating at optical frequencies, and thus the whole circuit is equally irradiated by the laser.

To overcome this difficulty, we propose a method to control the electronic properties of the metal nano tips under laser fields by tailoring the optical near field [1]. In particular, we focused on the fact that the electric field is enhanced around a tip apex. We experimentally and theoretically revealed that the tip radius is a critical parameter to determine the field enhancement factor: the smaller the tip radius, the larger the field enhancement factor. We also clarified how the complex dielectric constant of the material affects the field enhancement factor, which is a powerful guiding principle for choosing a material.

We employed this tip-radius dependence of the laser field enhancement factor to realize a diode structure consisting of two metal nano tips facing each other. Here, the radius of one tip (5 nm) was smaller than the other tip (11 nm). Due to the stronger field enhancement at the former tip, the electron emission yield was much larger than the other tip, although both tips were within a same laser spot. As a result, electrons are mainly emitted from the former tip under laser excitation, and this tip consequently works as a cathode. On the other hand, the other tip does not emit electrons and receives the electrons emitted from the cathode tip; thus works as an anode. The electrons flow from the cathode tip to the anode tip. When a bias voltage is applied between the two tips, this one-way current showed rectifying behavior to the bias voltage.

To summarize, we controlled electron emission properties of metal nano tips by tuning their tip radii to control the optical near fields, and achieved diode operation employing two metal tips with different radii.

References

1. S. Thomas, M. Krüger, M. Förster, M. Schenk and P. Hommelhoff "Probing of Optical Near-Fields by Electron Rescattering on the 1 nm Scale," Nano Lett. **13**, 4790 (2013).