Coherent Manipulation of Electrons in a Tunnel Junction with Carrier-Envelope Phase Controlled THz Electric Fields

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Abstract: We demonstrate that single-cycle terahertz electric fields manipulate the motion of electrons in a single tunnel junction. The direction of the electron tunneling through the junction strongly depends on the carrier-envelope phase of terahertz pulses.

OCIS codes: (240.7040) Tunneling; (270.1670) Coherent optical effects; (320.7110) Ultrafast nonlinear optics

1. Introduction

The latest advances in nanotechnology have made it possible to fabricate quantum nanocircuits and plasmonic devices [1]. In these devises, electron tunneling at subnanometer gap plays a crucial role for its functionalities. Therefore, improved control of electrons in a tunnel junction is indispensable for the development of next-generation quantum nanoelectronics.

Coherent control of electrons via the carrier-envelope phase (CEP) of ultrashort laser pulses is a promising way to overcome the bandwidth limitation of the modern electronics. Developing such an approach for a tunnel junction will provide new means to govern electrons on the nanoscale. The CEP-dependent control of electrons has been achieved using intense few-cycle near-infrared pulses [2,3]. However, these pulses can easily damage the tunnel junction due to thermal expansion because of its relatively high energy. Recently, we have shown that the electron tunneling can be controlled by the single-cycle terahertz (THz) electric fields in percolated Au nanostructures [4] without any thermal effects. Because of its huge nonlinearities, a combination of the tunnel junction and the single-cycle THz electric fields is highly expected to be a new platform of the CEP-controlled electronics. In this work, we demonstrate coherent manipulation of electrons in a tunnel junction using THz scanning tunneling microscopy (THz-STM) [5,6]. By tuning the CEP of single-cycle THz electric fields, direction of the electron tunneling was coherently controlled either from a nanotip to a sample or vice versa.

2. Experimental Setup

Figure 1 schematically illustrates the experimental setup for the THz-STM. The light source was a Ti-Sapphire regenerative amplifier with center wavelength of 800 nm, pulse duration of 130 fs and repetition of 1 kHz. Intense single-cycle THz electric fields were generated using a $LiNbO_3$ prism in a tilted-pulse-front configuration. The THz pulses were guided into one of two paths by tuning a removable gold-coated mirror: one was used for characterizing the THz waveforms by electro-optic sampling (EOS) and the other was used for delivering the THz pulses to a tunnel junction of the STM. For the passage to the STM, the THz pulses were focused onto the apex of an electrochemically etched Pt/Ir nanotip, which were polarized parallel to the nanotip. We used highly oriented pyrolytic graphite (HOPG) as a sample because of its atomically flat surface. All measurements were performed under ambient laboratory conditions.

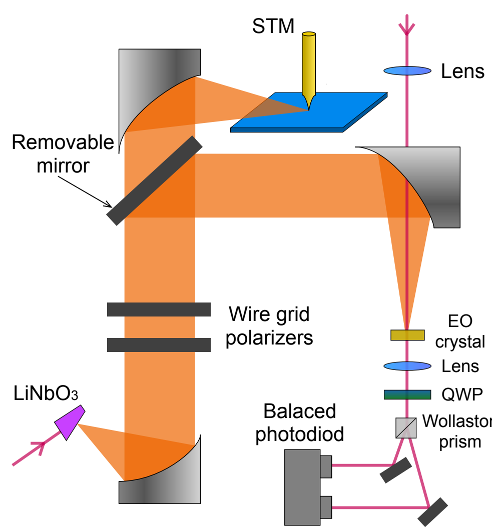

Fig. 1 Schematic of the experimental setup

3. Results and Discussion

As shown in Fig. 2(a), the CEP-controlled single-cycle THz electric field was successfully generated with different CEPs (ϕ_{CEP} = 0, π/2 and π) via the Gouy phase shift [7]. Figure 2(b) shows the CEP dependence of the tunnel current while sweeping the DC bias from 300 mV to -300 mV. The most remarkable feature in Fig. 2(b) is a series of THz-induced pulse trains,

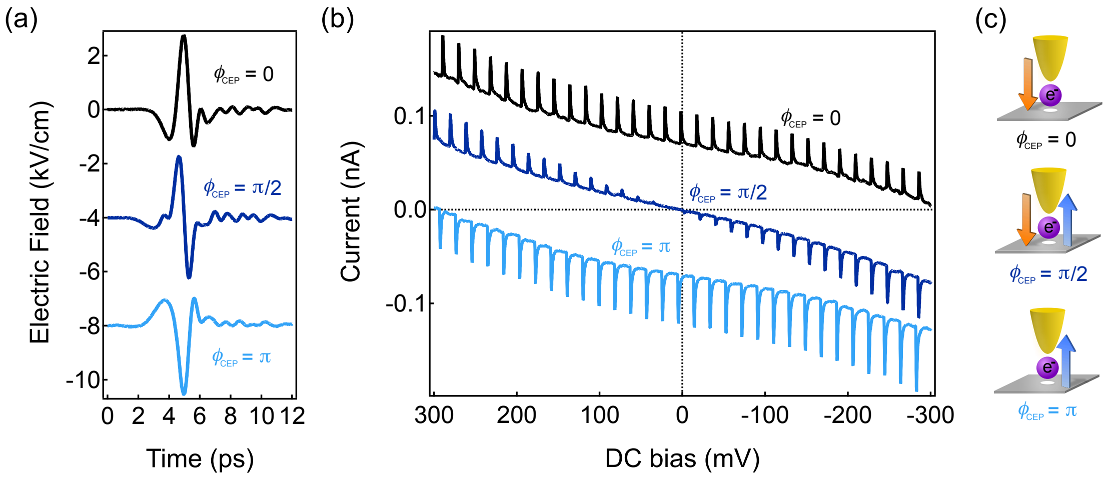

Fig. 2 (a) Waveforms of single-cycle THz electric fields with different CEPs (ϕ_{CEP} = 0, π/2 and π) measured using EOS. (b) CEP dependence of tunnel current as a function of DC bias measured using a digital oscilloscope. The spectra with ϕ_{CEP}=0 and π are offset by ±0.07 nA for clarity. (c) Schematics illustration of the electron tunneling processes through the junction. The orange and blue arrows show the tunneling direction.

which is a fingerprint of the ultrafast current bursts driven by THz electric fields. In the case of ϕ_{CEP} = 0, the pulse train takes a positive value, which corresponds to an electron tunneling from the nanotip to the sample. In the case of ϕ_{CEP} = π, on the other hand, the tunnel current shows the opposite behavior; the pulse train with a negative value indicates an electron tunnelling from the sample to the nanotip. In the case of ϕ_{CEP} = π/2, the direction of electron tunneling strongly depends on the DC bias; electrons undergo tunneling from the nanotip to the sample under the positive DC bias and in the opposite direction under the negative DC bias. The experimental data were analyzed based on the Simmons model [8] to discuss the dynamics of electron tunneling in a quantitative manner. From the analysis, we found the extremely huge enhancement of the THz electric field at the junction with a factor of 100,000 ± 10,000. We also revealed that enhanced THz electric field reaches 16 V/nm at the junction which is two times higher than the strongest THz electric field previously reported in free space [9]. This spatially confined intense single-cycle THz electric field can steer ~300,000 electrons in an extremely nonlinear regime on the subpicosecond timescale [6].

4. Conclusion

In conclusion, we have demonstrated coherent manipulation of electrons in a tunnel junction by utilizing CEP-controlled THz electric fields. Direction of the electron tunneling was coherently controlled either from a nanotip to a sample or vice versa by tuning the CEP of single-cycle THz electric fields. We believe that our concept provides a new platform for the ultrafast coherent control of electrons, and may inspire a new route towards designing future lightwave nanoelectronics.

5. References

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