A nanoscale vacuum-tube diode triggered by few-cycle laser pulses

Takuya Higuchi and Peter Hommelhoff

Lehrstuhl für Laserphysik, Friedrich-Alexander Universität Erlangen Nürnberg, Staudstraße 1, D-91058 Erlangen, Germany

takuya.higuchi@fau.de

Abstract: We propose and demonstrate a nanoscale vacuum-tube diode consisting of two metal nano-tips as an ultrafast electronic device employing pulsed electrons emitted by few-cycle photoemission.

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1. Introduction

A fundamental limitation for the operation speed of electronic devices is given by the bandwidth of the carrier response. Unlike carriers in solid-state devices which experience very fast decoherence and dephasing, the velocity of free electrons in vacuum is only limited by the speed of light. Vacuum-tube devices operate on the basis of the motion of free electrons in vacuum. Although integrated semiconductor technology has long rendered tube electronics unnecessary in modern information technology, vacuum tubes are still employed for high-frequency applications, such as radars.

Operation speed of the existing vacuum tubes is mainly limited by the temporal fluctuation in the thermally generated electron density and the traveling time of electrons between electrodes. Photoemission from metal nano-tips induced by few-cycle laser pulses bears the potential to significantly relax these limitations. Recently, above-threshold photoemission from metal nano-tips by few-cycle laser pulses has been observed, which ensures short duration of electron emission within laser pulse durations [1]. In addition, the laser field experiences geometrical field-enhancement, resulting in strongly localised field distribution at the end of the tip apex. This results in confinement of the electron emission spot, which enables us to form a nano-scale vacuum channel by approaching another tip in the proximity of the emitting tip apex. Reduction of the channel width reduces the traveling time of electrons.

In this contribution, we demonstrate a nano-scale vacuum-tube diode consisting of two metal nano-tips, which work as a cathode and an anode. We employ electrons emitted from metal nano-tips triggered by few-cycle laser pulses via prompt above-threshold photoemission, instead of thermally emitted electrons in conventional vacuum tube devices.

2. Methods

The cathode and the anode are two tungsten tips that are produced by electro-chemical etching from a polycrystalline tungsten wire. The cathode tip has a radius of curvature of less than 5 nm, as observed by the field ion microscopy. The anode tip is blunter and hence exhibits a weaker field enhancement at the tip apex, suppressing both field- and photo-emission compared to the cathode tip. The tips are placed in an ultrahigh vacuum chamber with a base pressure of 3×10^{-8} Pa. Figure 1(a) shows schematics of the experimental setup. The cathode tip is mounted on a 3d piezo-electric translational stage and faces the fixed anode tip. We align the two tips on a same axis and bring them in a distance of $d = 300 \pm 100$ nm with the help of the DC-field emission current between the two tips, which depends sensitively on the relative position of the tips.

We use two-optical-cycle laser pulses from a Ti:Sapphire laser oscillator with a repetition rate of 80 MHz and a centre frequency of 780 nm. The pulse duration is 5.2 fs, as determined from the interferrometric autocorrelation trace. The laser beam is focused on the cathode tip by an off-axis parabolic mirror, which is mounted on another piezo-electric stage [Fig 1(b)]. Electrons are emitted by absorption of at least three photons of energy $\hbar\omega \sim 1.58$ eV because the work function of tungsten is 4.35 eV at the W(310) facet. Above-threshold photoemission process generates electrons with kinetic energies up to ~ 9 eV as inferred from retarding field measurements. The electrons emitted from the cathode are collected by the anode tip. We employ lock-in amplification to measure the current, for which the laser beam is chopped at a modulation frequency of 1.7 kHz. The current from the anode is pre-amplified and converted to voltage, and integrated by a lock-in amplifier, which allows us to achieve a sensitivity of 5×10^{-2} fA after averaging over 10 s.

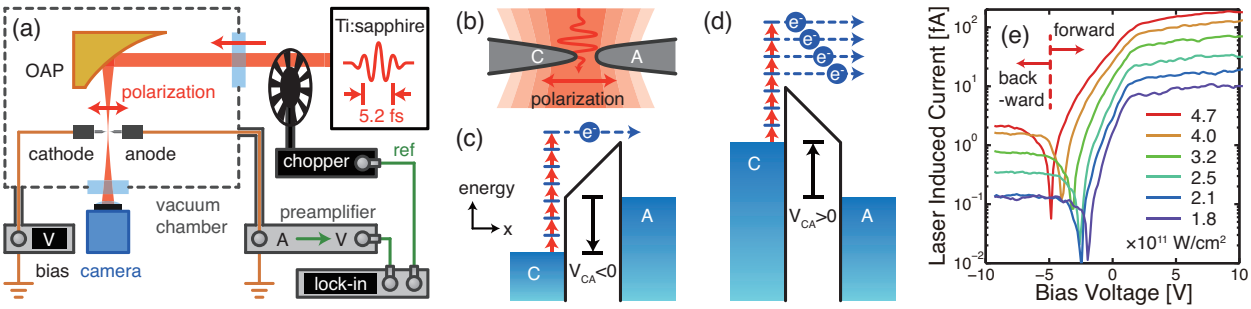

Fig. 1. (a) Schematic of the experimental setup and (b) magnified view around the tip apexes (C: cathode, A: anode). Energy diagrams of the laser-injected diode in (c) reverse-bias and (d) forward-bias operations. (e) Current-voltage characteristic curves of the diode triggered by laser pulses with various intensities. Note the current switches sign at the kink in the log-plot.

3. Results and Discussions

Figure 1(e) shows the measured current between the laser-triggered cathode and the anode tips as a function of the bias voltage V_{CA} between them. The current nonlinearly depends on the bias voltage and shows a rectifying behaviour. The forward saturation current is larger than the reverse saturation current by two-orders of magnitude for the largest laser intensity (4.7×10^{11} W/cm^2 nomimal laser intensity in the bare focus, i.e. without field enhancement). The mechanism of diode operation is explained using the energy diagrams depicted in Fig. 1(c) and (d). Electrons are emitted through multi-photon photoemission. When a reverse bias is applied [Fig.1 (c)], the current is reduced because only the electrons having higher energies than the potential barrier can reach the anode. On the other hand, a forward bias allows all the electrons that overcome the work function to flow. The weak current in strong reverse bias conditions results from the weak emission from the anode tip (note that the current switches sign in the log-plot). The short-circuit current increases as the laser intensity increases.

When a reverse bias is applied, only electrons with higher energy than the bias potential can reach the anode. This determines the lowest initial velocity and thus the longest travelling time τ_L of electrons that contribute to the current. Assuming a planner-capacitor potential, a tip distance of $d = 300$ nm and $V_{\mathrm{CA}} = -4$ V yields a conservative estimate of $\tau_L = 450$ fs. The photoemission process is in the time scale of pulse duration (5.2 fs). Thus the whole process including the electron emission and flow between two electrodes completes within femtosecond timescales.

4. Conclusion and Outlook

We observed rectifying behaviour between two metal nano-tips, where the electrons are emitted from the cathode tip through multi-photon photoemission by few-cycle laser pulses. This diode device operates in femtosecond timescales, owing to the short duration of the electron emission process, the comparably high initial kinetic energy of the emitted electrons, and the sub-micron distance between the two electrodes. In the strong-field regime, electron emission from nano-tips depends on the carrier-envelope phase of few-cycle laser pulses, providing the possibility to steer emission process on attosecond timescales [2]. In addition, the two-tip distance can be further decreased down to the regime of quantum tunnelling [3]. Together with these advanced methods, our achievement of diode operation with metal nano-tips has the potential to operate on attosecond timescales. The current status of the experiment will be reported.

References

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