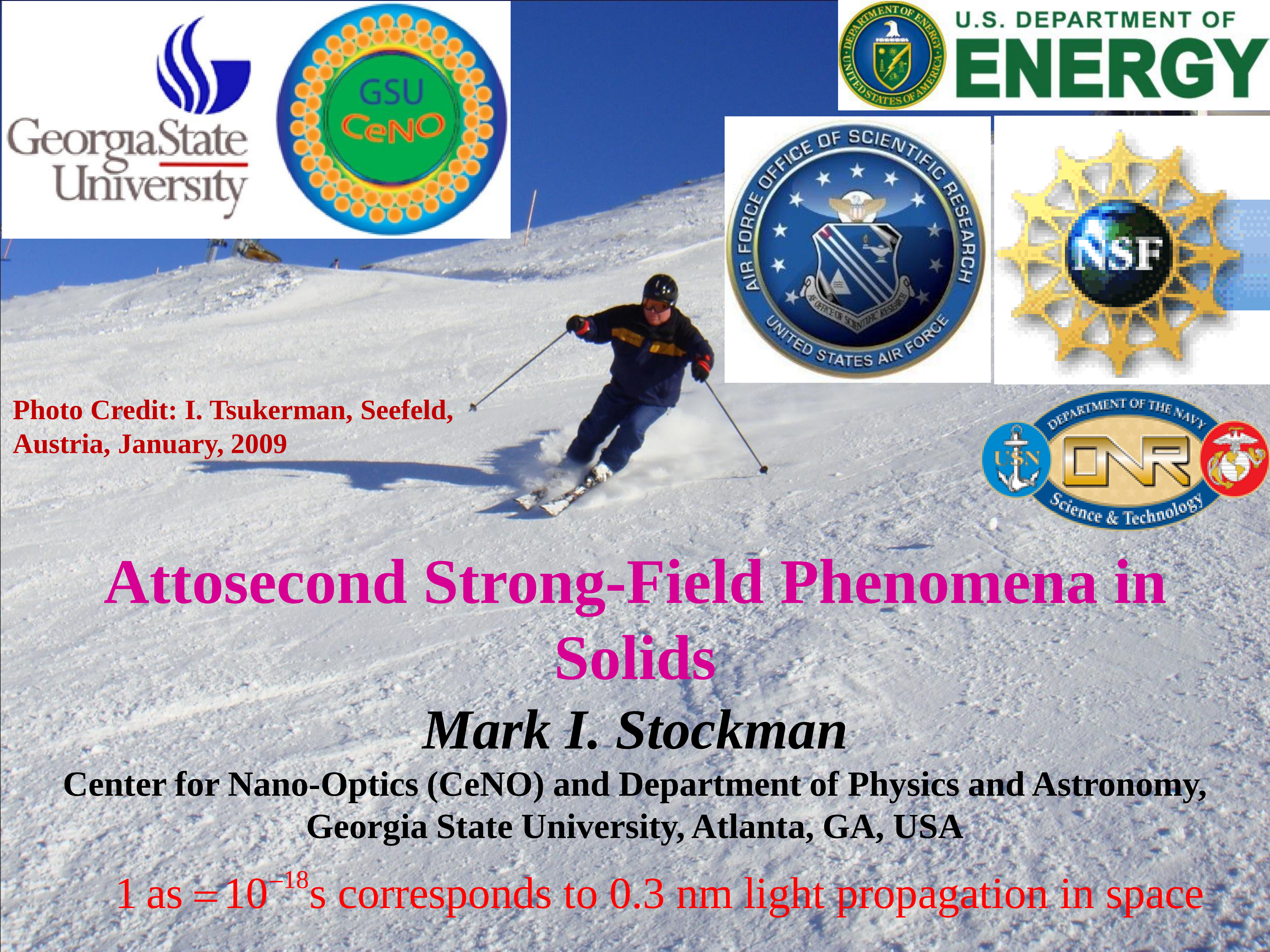


Photo Credit: I. Tsukerman, Seefeld, Austria, January, 2009

Attosecond Strong-Field Phenomena in Solids

Mark I. Stockman

Center for Nano-Optics (CeNO) and Department of Physics and Astronomy, Georgia State University, Atlanta, GA, USA

$1\ \text{as} = 10^{-18}\text{s}$ corresponds to 0.3 nm light propagation in space

CONTENTS

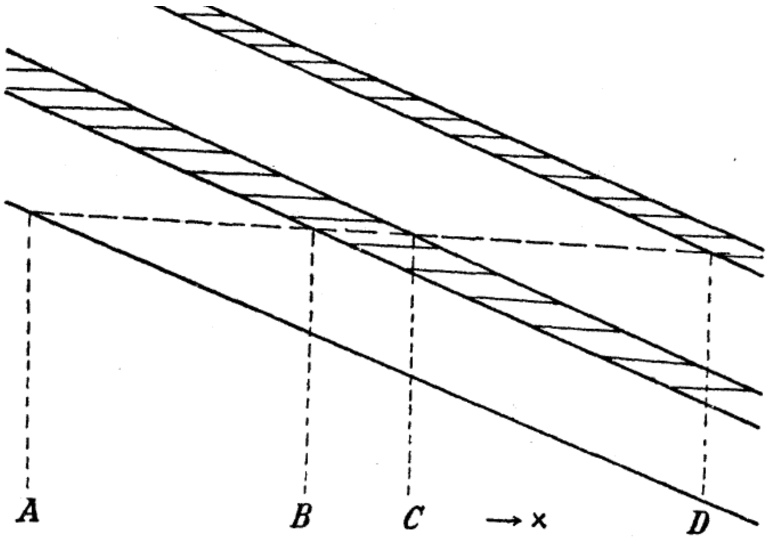
- Introduction; strongly nonlinear phenomena in condensed matter in high fields: Zener breakdown, MOSFETs and field control of solids
- Adiabatic states of a solid in strong field
- **Reversible attosecond photocurrents and (semi)metallization of dielectrics**
- **Attosecond field control of dielectrics**
- **High-field attosecond behavior of graphene and semiconductors**
- **Conclusions**

PROCEEDINGS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A Theory of the Electrical Breakdown of Solid Dielectrics

Clarence Zener

Proc. R. Soc. Lond. A 1934 **145**, 523-529



$$\gamma = \frac{eFa}{h}\exp-\left\{\frac{\pi^2}{h^2}\frac{ma\varepsilon^2}{|eF|}\right\}$$

FIG. 1.—“Potential barrier” diagram. The shaded regions represent zones of forbidden energy in the presence of an electric field.

Stationary field, bulk solid

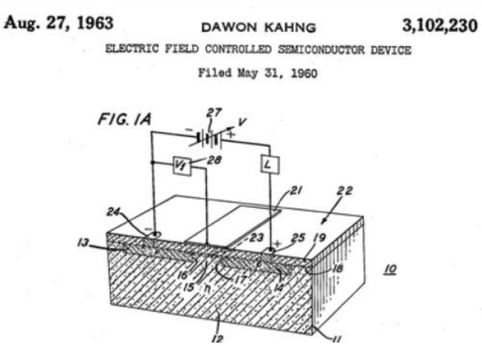
The most important technology: Information processing

P. Packan et al., in 2009 IEEE International Electron Devices Meeting (IEDM), *High Performance 32nm Logic Technology Featuring Second Generation High-K + Metal Gate Transistors (Baltimore, MD, 2009), Vol. IEDM09-662, p. 28.4.1-28.4.4*

Abstract:

A 32nm logic technology for high performance microprocessors is described. 2nd generation high-k + metal gate transistors provide record drive currents at the tightest gate pitch reported for any 32 nm or 28nm logic technology. NMOS drive currents are 1.62mA/um Idsat and 0.231mA/um Idlin at 1.0V and 100nA/um Ioff. PMOS drive currents are 1.37mA/um Idsat and 0.240mA/um Idlin at 1.0V and 100nA/um Ioff. The impact of SRAM cell and array size on Vccmin is reported.

MOSFET US Patent



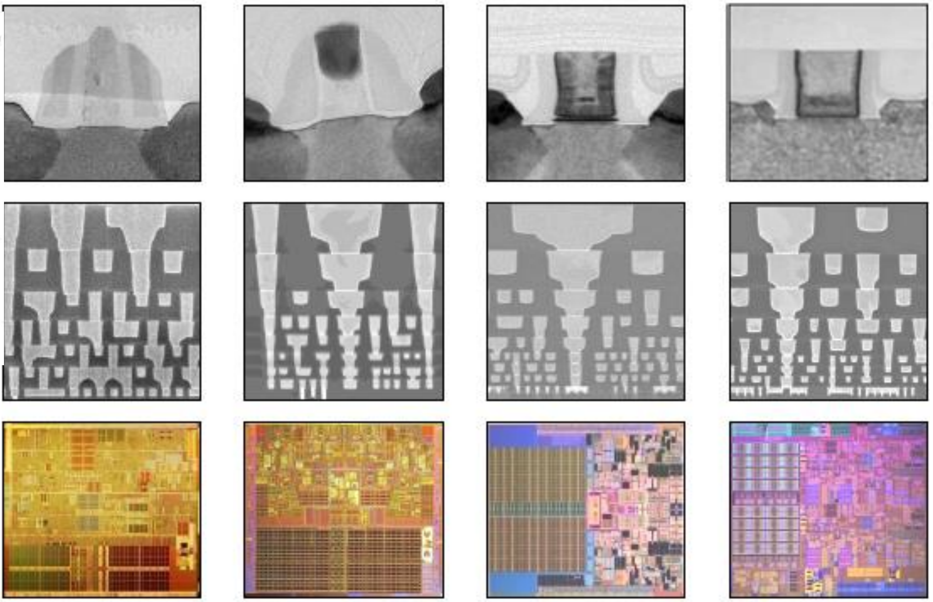
Aug. 27, 1963 DAWON KAHNG 3,102,230

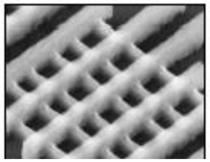
ELECTRIC FIELD CONTROLLED SEMICONDUCTOR DEVICE

Filed May 31, 1960

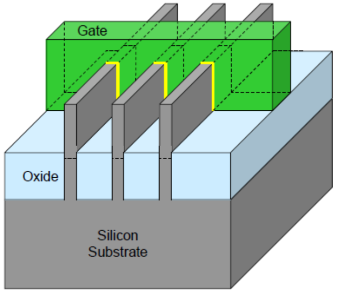
Speed ~ 100-300 GHz
Low resistance to ionizing radiation

90 nm	65 nm	45 nm	32 nm	22 nm
2003	2005	2007	2009	2011





22 nm Tri-Gate Transistor



Tri-Gate transistors can have multiple fins connected together to increase total drive strength for higher performance

Processor speed : **Transistor speed is not a limiting factor! Charging the interconnects is.**

$$f_{\max} = I_{\text{drive}} / \left(C_{\text{Intercon}} \Delta U \right) \sim 3\ \text{GHz}$$

All optical processing is a necessity

nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 28 FEBRUARY 2014 | DOI: 10.1038/NPHOTON.2014.28

Attosecond metrology: from electron capture to future signal processing

Ferenc Krausz[1,2] and Mark I. Stockman[1,2,3]

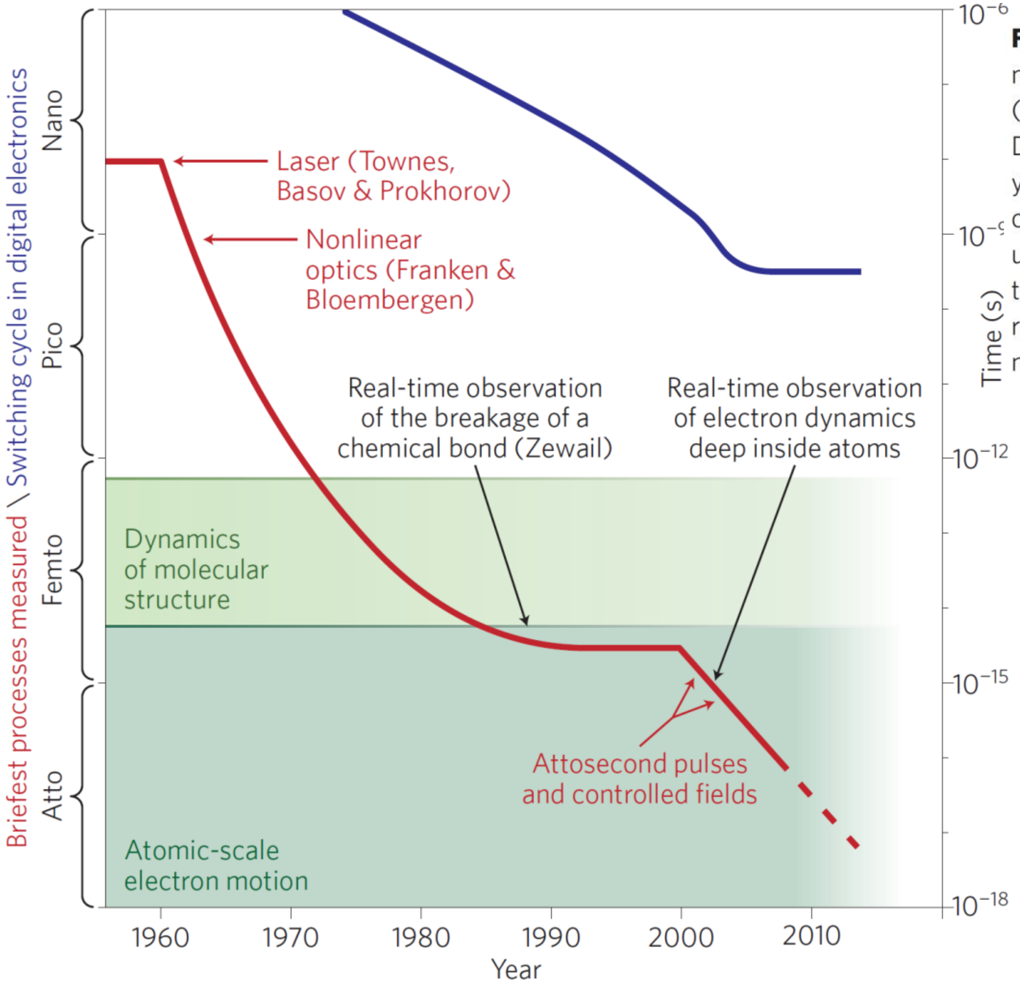


Figure 1 | Evolution of ultrafast science and digital electronics. Briefest measured time intervals (lower red line) and shortest switching cycle (inverse of the clock rate) of digital processors (upper blue line). Discontinuities in the derivative of the briefest measured interval against year curve indicate revolutions in ultrafast metrology. In the early 1960s, coherent light waves generated by lasers and nonlinear optical effects were used to produce ultrashort pulses from these waves. At the beginning of the new millennium, attosecond pulse generation and measurement[18] were realized, and controlled light fields for precision attosecond control[28] and metrology[34] were generated.

A

ı/stockman

solids

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Fundamental Adiabatic Phenomena in Strong Fields

For an insulator, optical field is adiabatic with respect to the bandgap which greatly exceeds the optical frequency, $\hbar\omega \ll \Delta_g$.

As the field increases, it closes bandgap at a critical amplitude

$$F_g \sim \frac{\Delta_g}{ea} \sim \frac{10\text{ eV}}{e\,5\text{ Å}} \sim 2\frac{\text{V}}{\text{Å}},$$ where Δ_g is bandgap, and a is lattice period

Under these conditions, electrons are localized wave packets (Wannier-Stark localization). Their levels form an equidistant ladder with the Bloch-frequency spacing, $\hbar\omega_B = eFa;$

For $F \gtrsim F_g = \dfrac{\Delta_g}{ea}$, $\hbar\omega_B \gtrsim \Delta_g \gg \hbar\omega$, and adiabaticity sets on

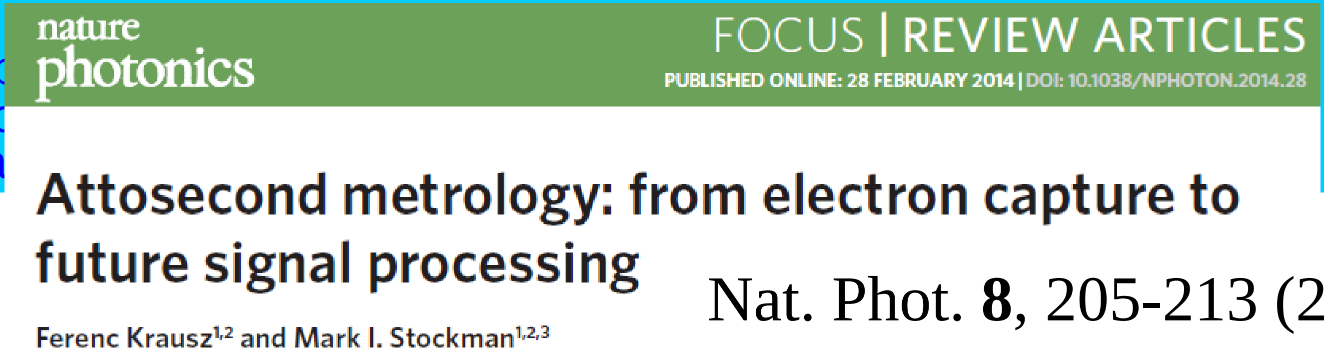
Thus the bandgap ultimately limits and determines the fastest possible reversible (adiabatic) process at *both* low and high fields:

$$\boxed{\tau \gtrsim \Delta_g^{-1}}$$

In solids, a characteristic energy in high fields is $\hbar\omega_B = eFa$

In atoms, a characteristic energy in high fields is $U_p \sim \dfrac{(eF)^2}{m\omega^2}$

This dramatic difference is due to the Wannier-Stark localization in strong adiabatic fields



nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 28 FEBRUARY 2014 | DOI: 10.1038/NPHOTON.2014.28

Attosecond metrology: from electron capture to future signal processing

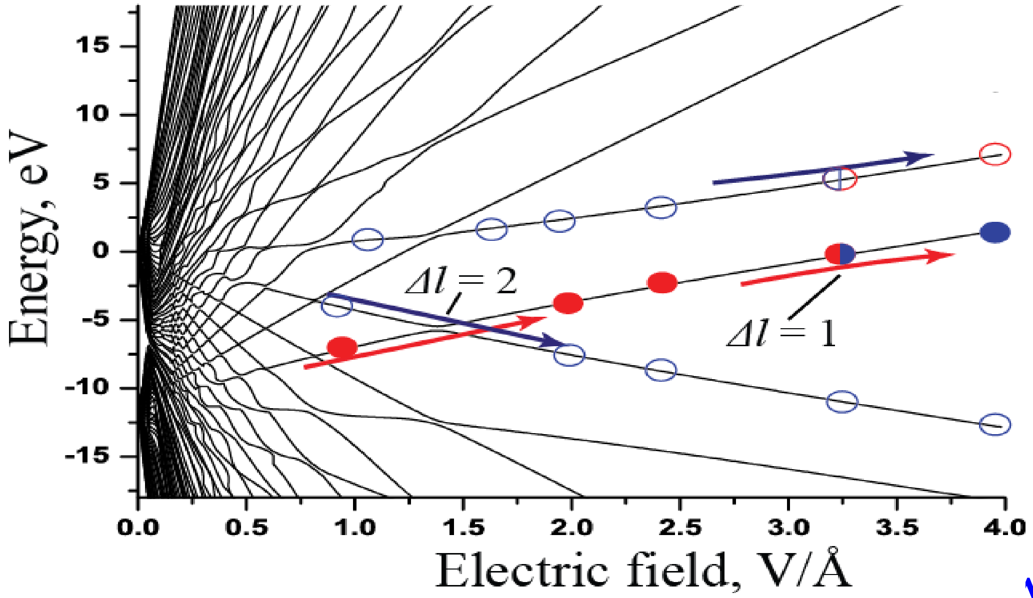
Ferenc Krausz[1,2] and Mark I. Stockman[1,2,3]

Nat. Phot. **8**, 205-213 (2014).

In a strong ultrafast optical field, an *n*-anticrossing (Zener-type transition) with a tunneling across Δ*l* lattice periods and transition into the empty conduction band occurs at a field

$$E \sim \frac{\Delta_g}{\Delta l\ e\ a} \sim \frac{2}{\Delta l}\ \frac{\text{V}}{\text{Å}},\ \text{where } \Delta_g \text{ is bandgap, and } a \text{ is lattice period}$$

Adiabatic Wannier-Stark levels in a strong field for valence and conduction bands of silica



LETTER

doi:10.1038/nature11567

Optical-field-induced current in dielectrics

Agustin Schiffrin[1]†, Tim Paasch-Colberg[1], Nicholas Karpowicz[1], Vadym Apalkov[2], Daniel Gerster[3], Sascha Mühlbrandt[1,3], Michael Korbman[1], Joachim Reichert[3], Martin Schultze[1,4], Simon Holzner[1], Johannes V. Barth[3], Reinhard Kienberger[1,3], Ralph Ernstorfer[1,3,5], Vladislav S. Yakovlev[1,4], Mark I. Stockman[2] & Ferenc Krausz[1,4]

[1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany. [2]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia 30340, USA. [3]Physik-Department, Technische Universität München, James-Franck-Strasse, D-85748 Garching, Germany. [4]Fakultät für Physik, Ludwig-Maximilians-Universität, Am Coulombwall 1, D-85748 Garching, Germany. [5]Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4–6, 14195 Berlin, Germany. †Present addresses: Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1 Canada; Quantum Matter Institute, University of British Columbia, Vancouver, British Columbia, V6T 1Z4 Canada.

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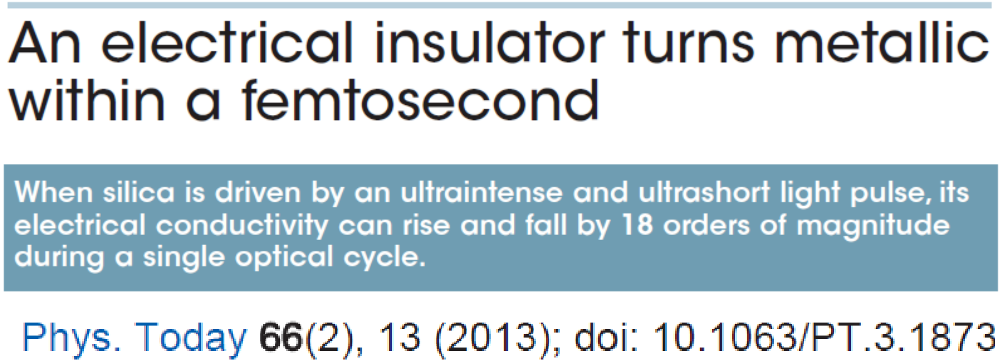
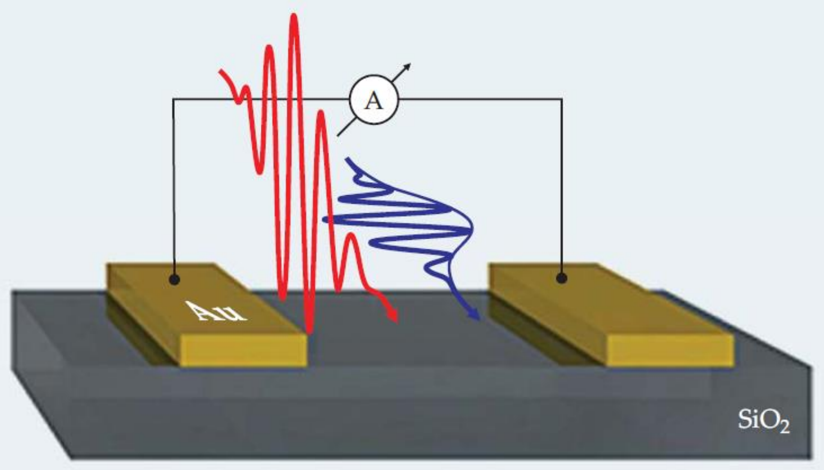


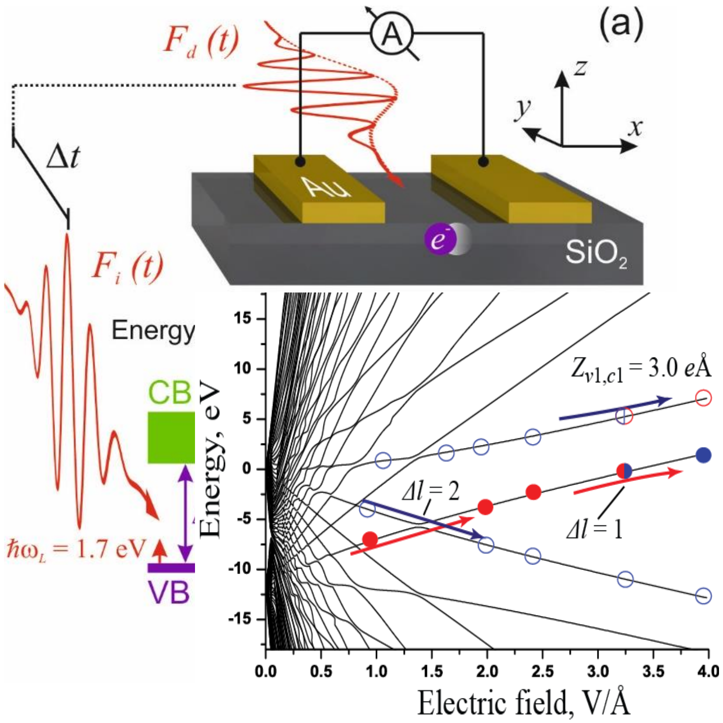
An electrical insulator turns metallic within a femtosecond

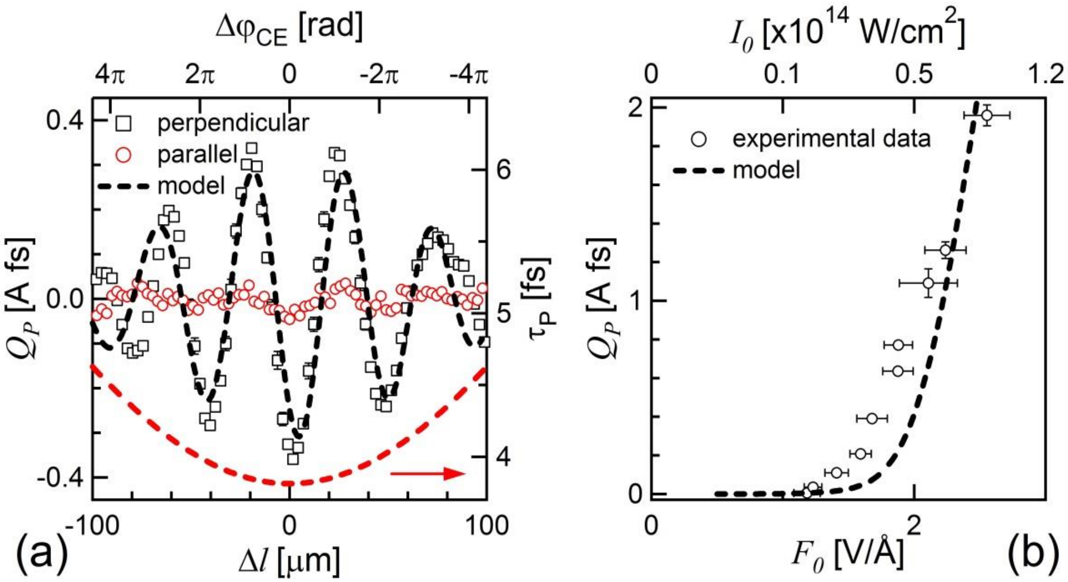
When silica is driven by an ultraintense and ultrashort light pulse, its electrical conductivity can rise and fall by 18 orders of magnitude during a single optical cycle.

Phys. Today **66**(2), 13 (2013); doi: 10.1063/PT.3.1873



Single-pulse field-induced current experiment in silica





Optical-field-induced conductivity and current control in a dielectric

Carrier-envelope-phase control and intensity dependence of optical-field-generated electric current in SiO_2.

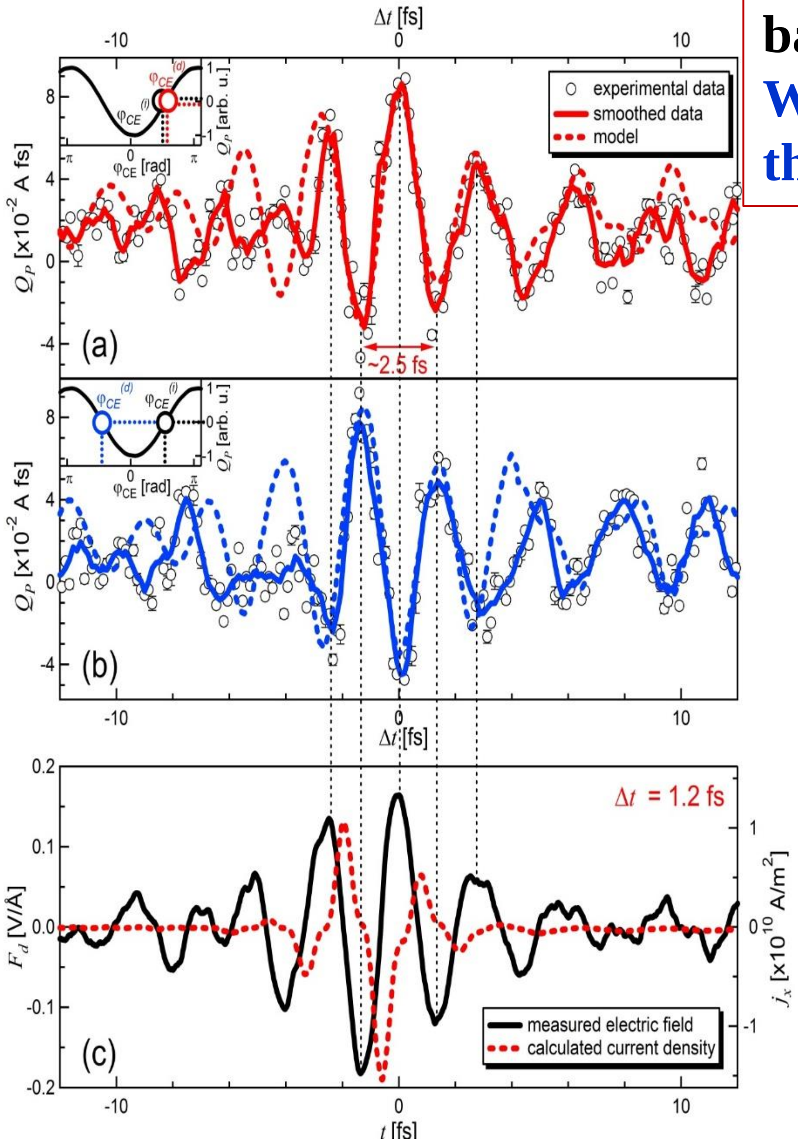
Peak current ~1 A.

Conductivity increased by **>18 orders of magnitude** compared to to silica

Double-pulse experiment:

Strong field is normal to the direction between the electrodes, "metallizes" (closes the bandgap) the dielectric

Weak field is parallel to the direction between the electrodes, driving current



Sub-femtosecond control of electric current with the electric field of light.

(a)-(b) Transferred charge versus delay between the injection and drive pulses.

(c) Real-time optical electric field of the VIS/NIR pulses retrieved from attosecond streaking .The red dashed curve displays the time-dependent current density as calculated from quantum mechanical theory

Excitation with 4-fs near-ir/vis pulse, detection with attosecond-XUV absorption

LETTER

doi:10.1038/nature11720

Controlling dielectrics with the electric field of light

Martin Schultze[1,2], Elisabeth M. Bothschafter[1,3], Annkatrin Sommer[1], Simon Holzner[1], Wolfgang Schweinberger[1], Markus Fiess[1], Michael Hofstetter[2], Reinhard Kienberger[1,3], Vadym Apalkov[4], Vladislav S. Yakovlev[2], Mark I. Stockman[4] & Ferenc Krausz[1,2]

[1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany. [2]Fakultät für Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, D-80539 München, Germany. [3]Physik-Department, Technische Universität München, James-Franck-Strasse, D-85748 Garching, Germany. [4]Department of Physics, Georgia State University, Atlanta, Georgia 30340, USA.

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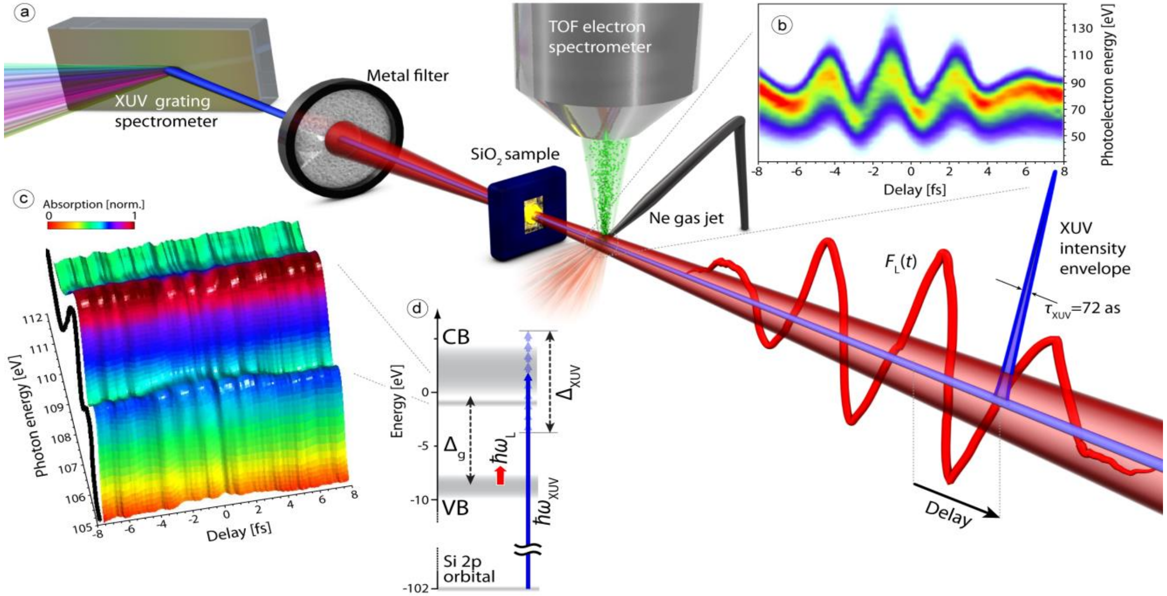
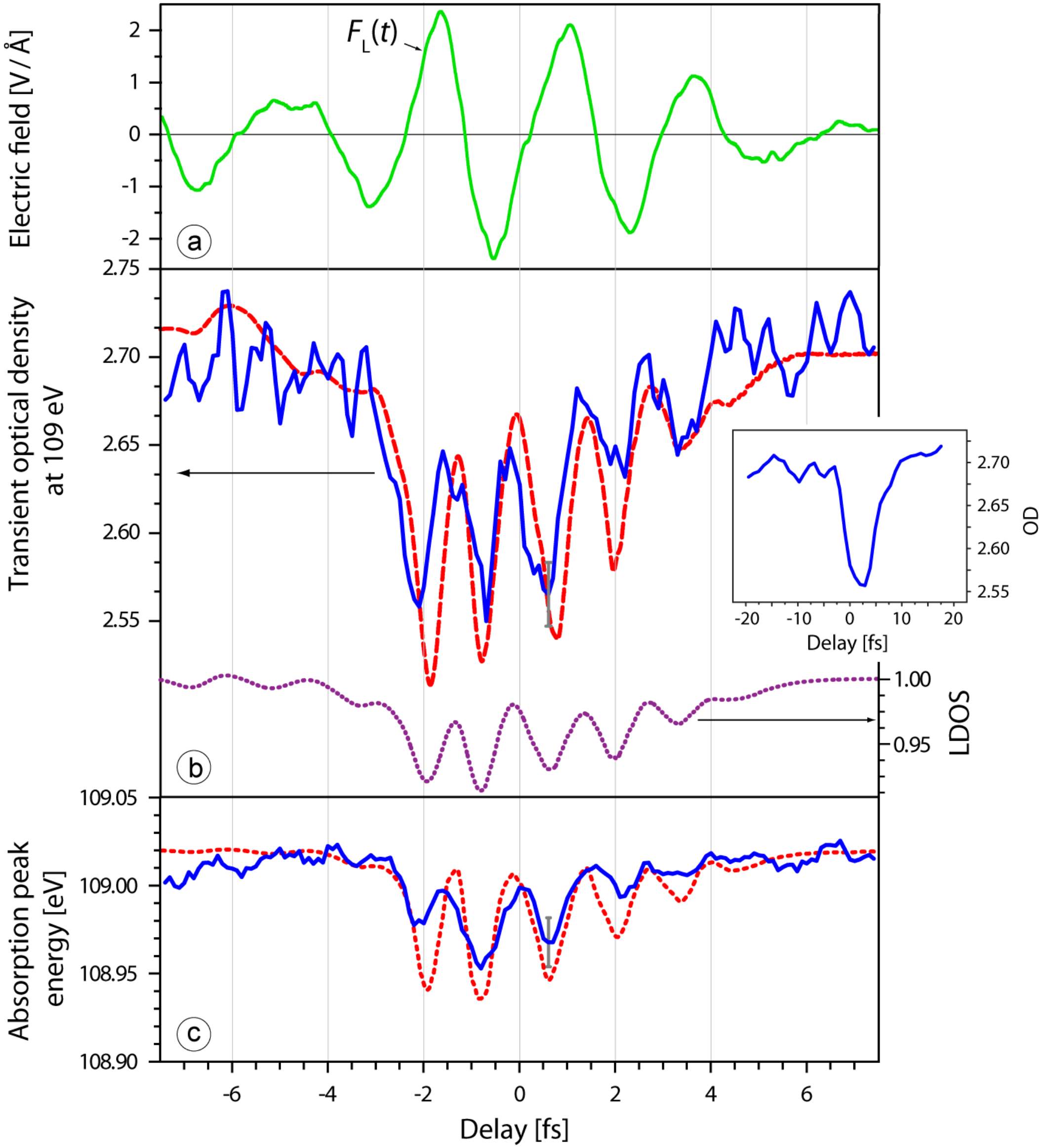


Reversible XUV absorption in silica

Field-driven processes



Attosecond time-resolved strong-field-induced effects in SiO_2. Solid lines, experimental results; dashed lines, predictions of theoretical modeling.

(a) Electric field of the few-cycle NIR laser pulse impinging on the SiO_2 sample, $F_L(t)$, as extracted from attosecond streaking (see Fig. 1b).

(b) Transient change of the OD integrated as a function of the delay between the 72-as XUV probe and the NIR laser pulse (blue solid line), along with the prediction of quantum mechanical model (red dashed line). The inset shows the OD evolution in a more extended delay range, recorded with larger delay steps (0.5 fs). Dashed violet line: Calculated local density of states (LDOS) at the position of a Si atom (integrated over the energy range accessed by the XUV pulse, for more details, see SI) versus delay of the XUV probe.

(c) Energy of the absorption peak at 109 eV subject to an optical-field-induced (ac-Stark) shift (measurement: blue solid line, calculation: red dashed line

Attosecond strong-field phenomena in solids

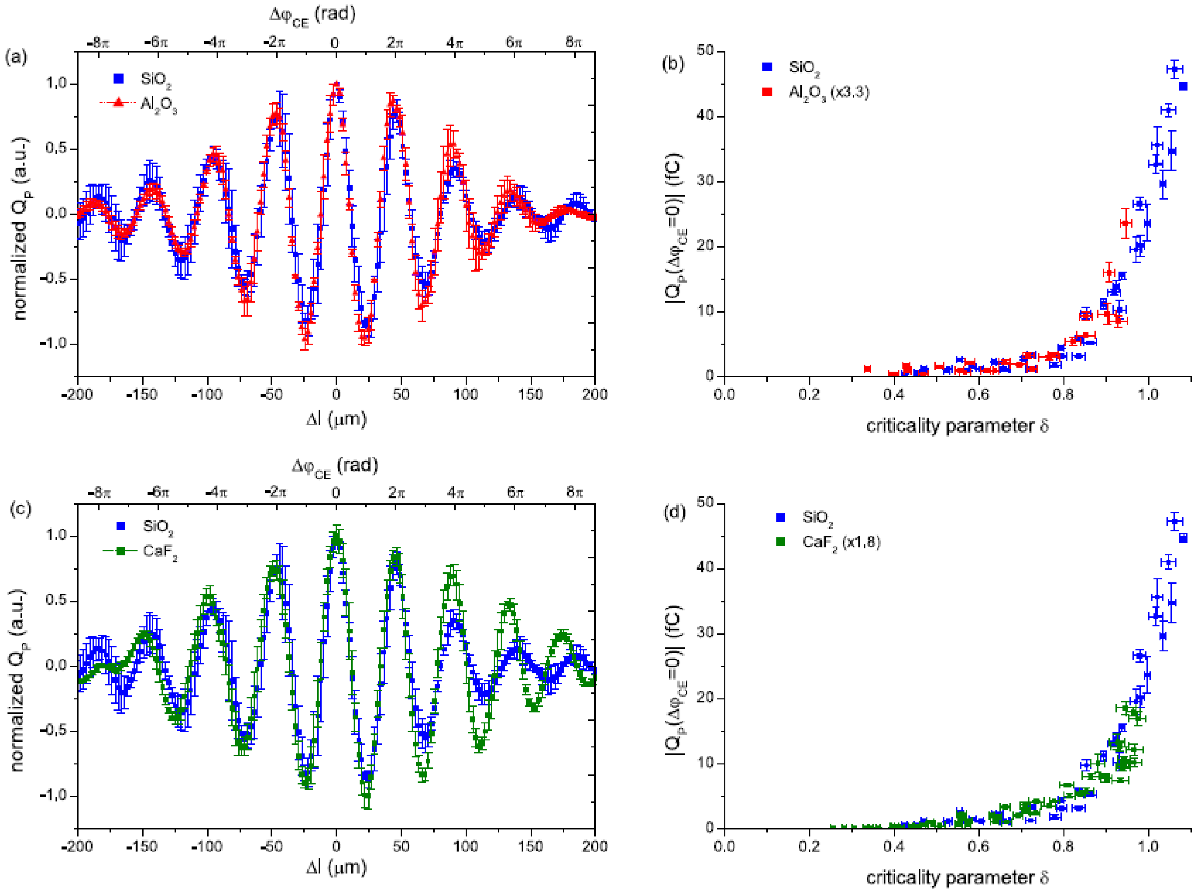
SCIENTIFIC REPORTS

OPEN

Semimetallization of dielectrics in strong optical fields

Ojoon Kwon[1,2], Tim Paasch-Colberg[3,†], Vadym Apalkov[4], Bum-Kyu Kim[5,‡], Ju-Jin Kim[5], Mark I. Stockman[4] & D. Kim[1,2]

Sci. Rep, **6, 21272-1-9 (2016).**



$$\delta = \frac{F_0}{F_g}, \quad F_g = \frac{\Delta_g}{ea}$$

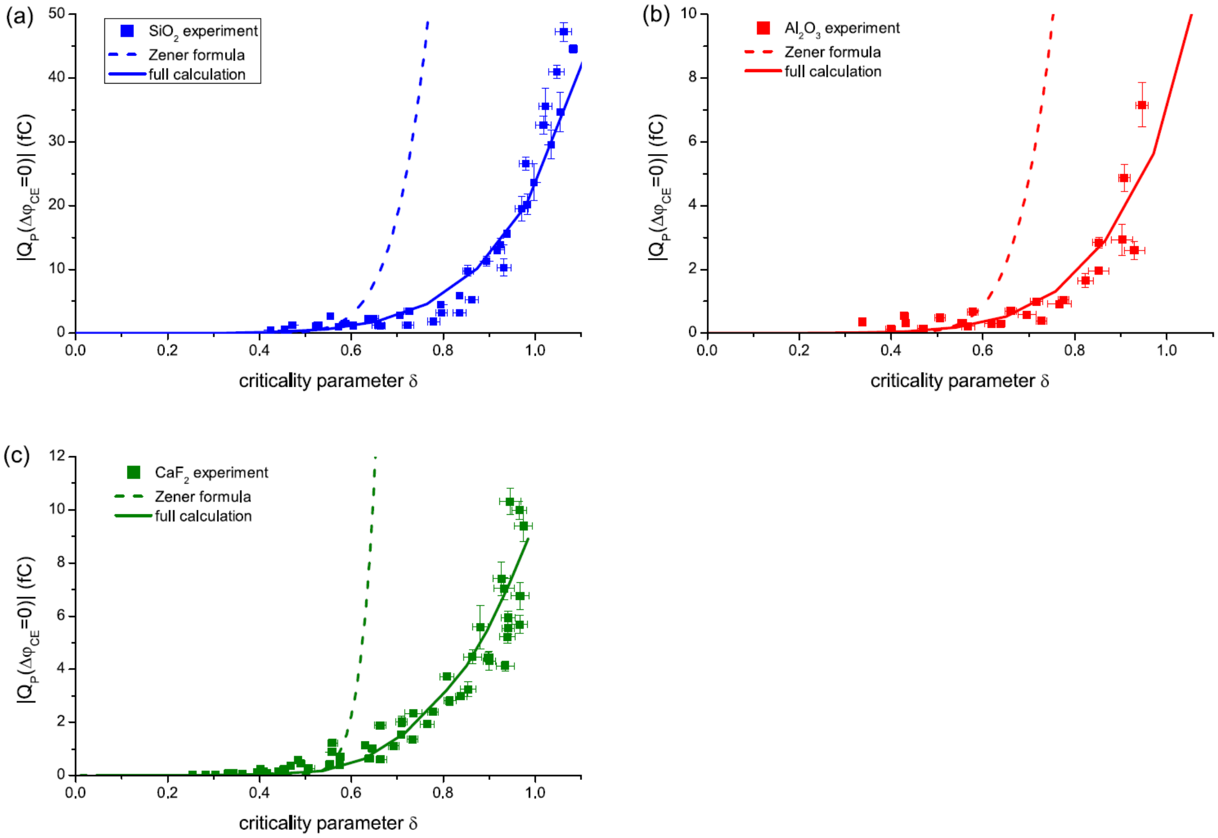


Figure 3. Measured maximum transferred charge $|Q_P(\Delta\varphi_{CE} = 0)|$ as a function of δ (squares); fitting based on Zener-Keldysh interband tunneling formula (dashed) and theoretical computations (described in the text) including both interband and intraband transition (solid) for (**a**) quartz, (**b**) sapphire and (**c**) calcium fluoride. Error bars represent the same information as described in the caption of Fig. 2b.

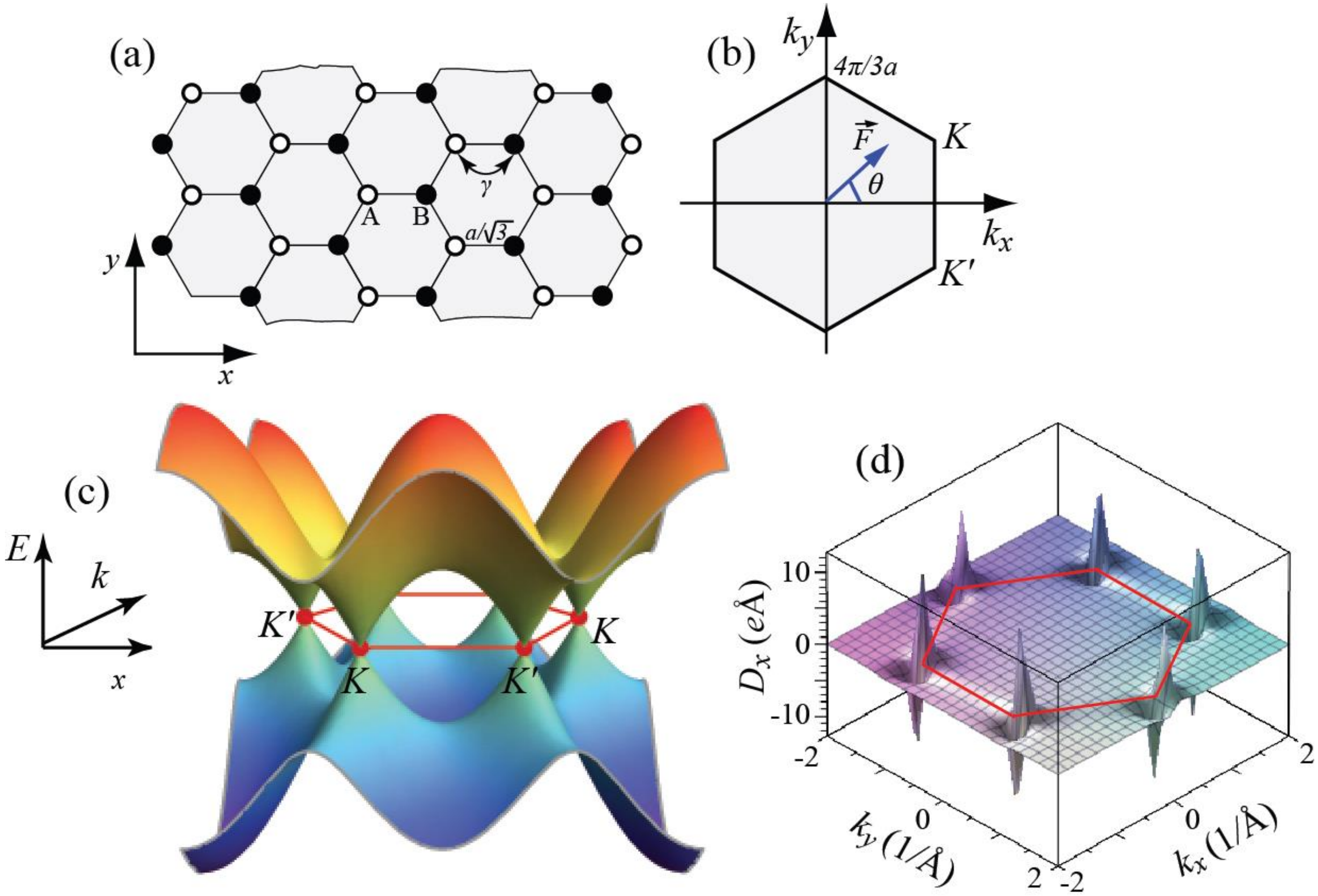
Following instantaneous electric field of optical wave is the consequence and unambiguous sign of adiabaticity.

Returning to the original state after the pulse is another strong evidence of adiabatic following.

Adiabaticity = Reversibility

Adiabaticity → Universality

Ultrafast Strong-Field Phenomena in Graphene and Semiconductors



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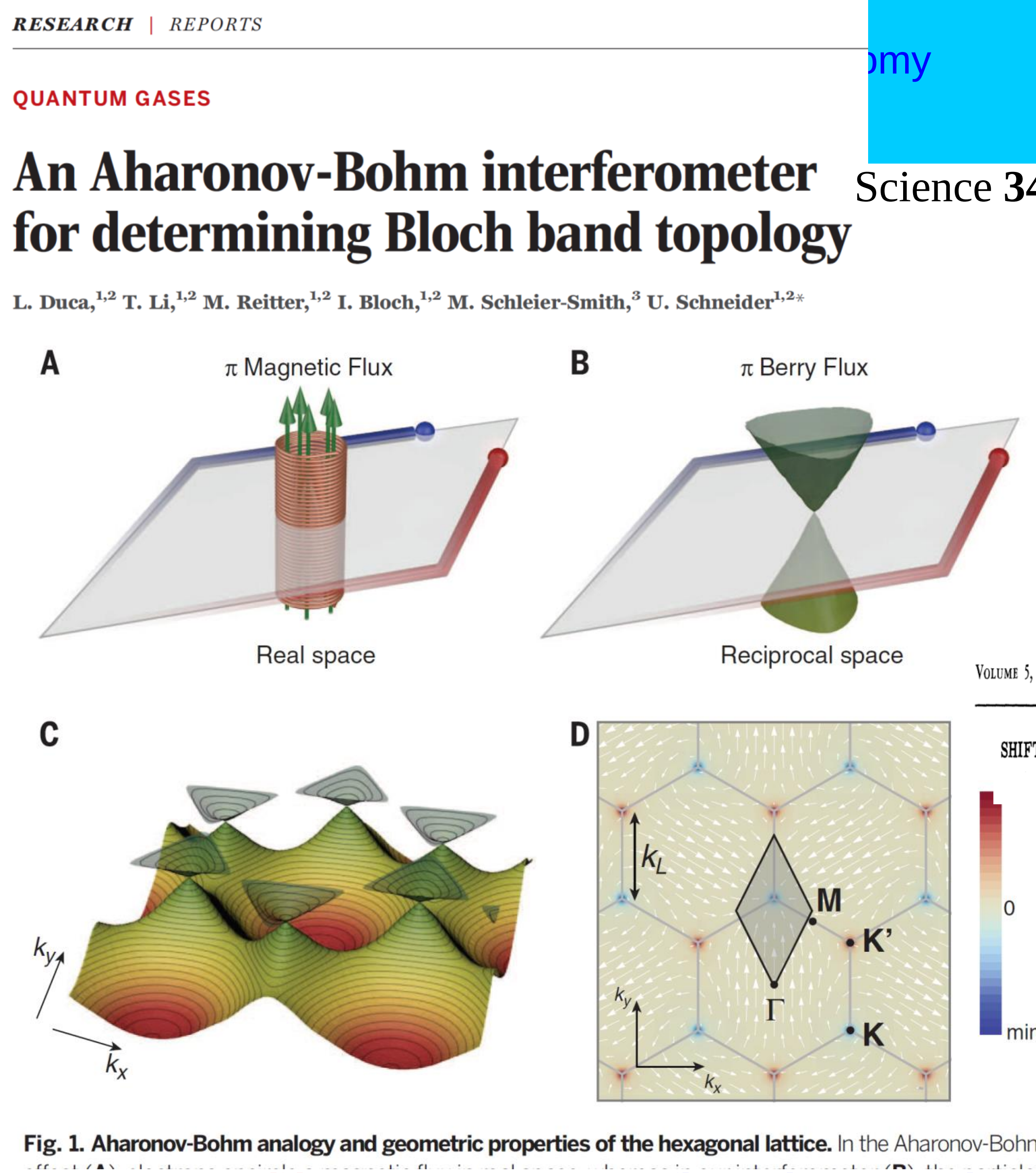

RESEARCH | REPORTS

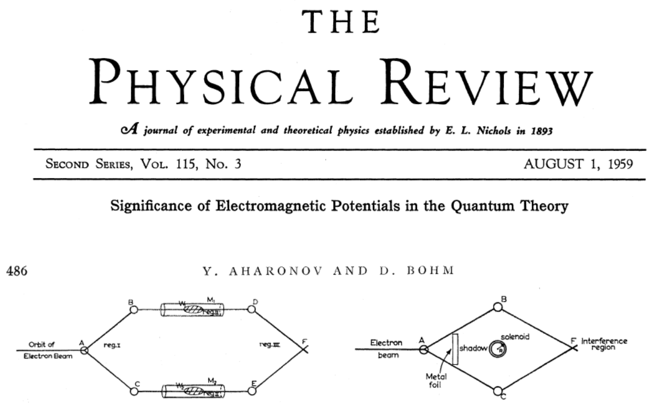
QUANTUM GASES

An Aharonov-Bohm interferometer for determining Bloch band topology

L. Duca,[1,2] T. Li,[1,2] M. Reitter,[1,2] I. Bloch,[1,2] M. Schleier-Smith,[3] U. Schneider[1,2]*

Fig. 1. Aharonov-Bohm analogy and geometric properties of the hexagonal lattice. In the Aharonov-Bohm

Science **347**, 288-292 (2015).

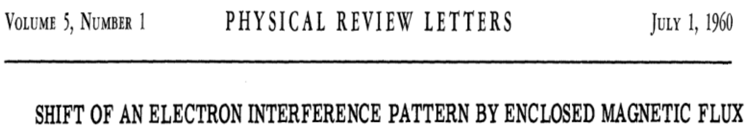

THE PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 115, NO. 3 AUGUST 1, 1959

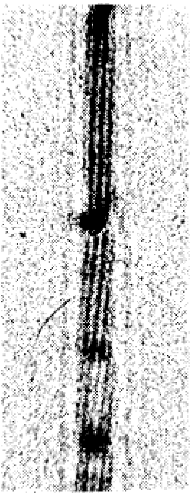
Significance of Electromagnetic Potentials in the Quantum Theory

486 Y. AHARONOV AND D. BOHM


VOLUME 5, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1960

SHIFT OF AN ELECTRON INTERFERENCE PATTERN BY ENCLOSED MAGNETIC FLUX

R. G. Chambers



Atom Workshop

Dresden (Germany) 12/ AM

solids

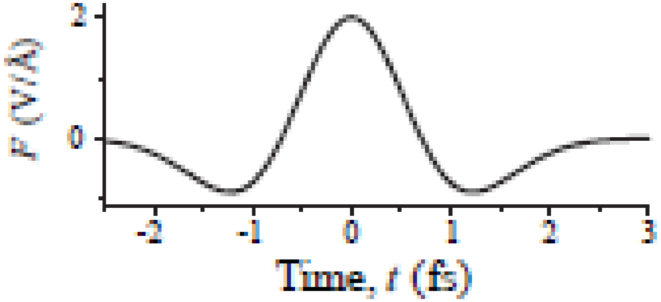
E-mail: mstockman@gsu.edu

PHYSICAL REVIEW B **91**, 045439 (2015)

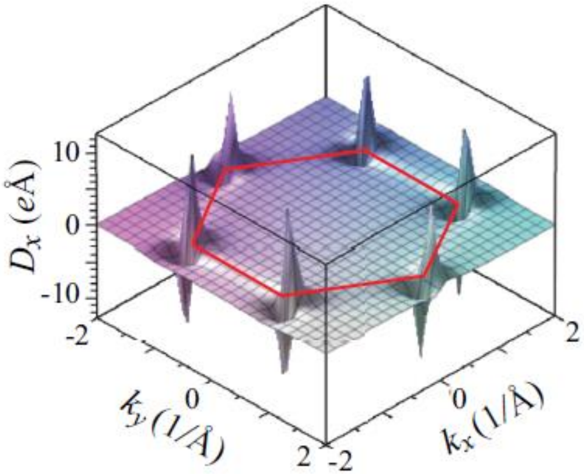
Graphene in ultrafast and superstrong laser fields

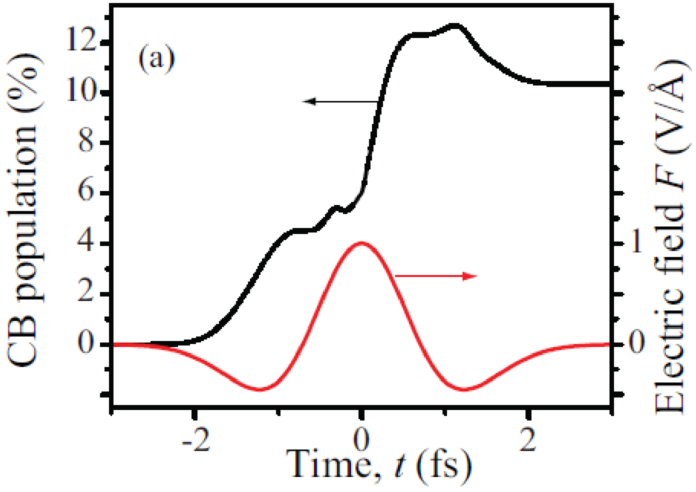
Hamed Koochaki Kelardeh,[1] Vadym Apalkov,[1] and Mark I. Stockman[1,2,3]

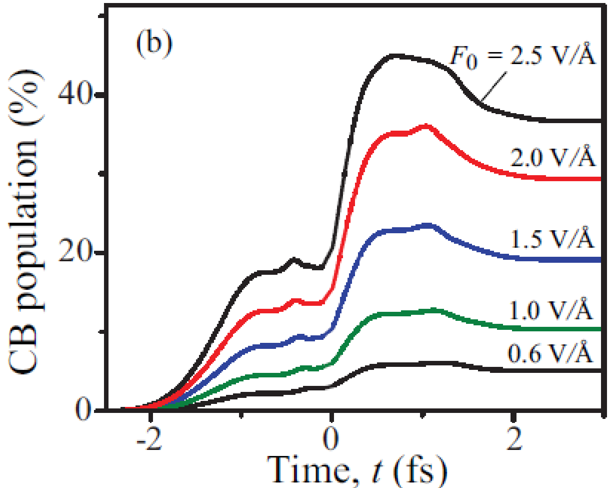
Pulse shape



Interband dipole matrix elements

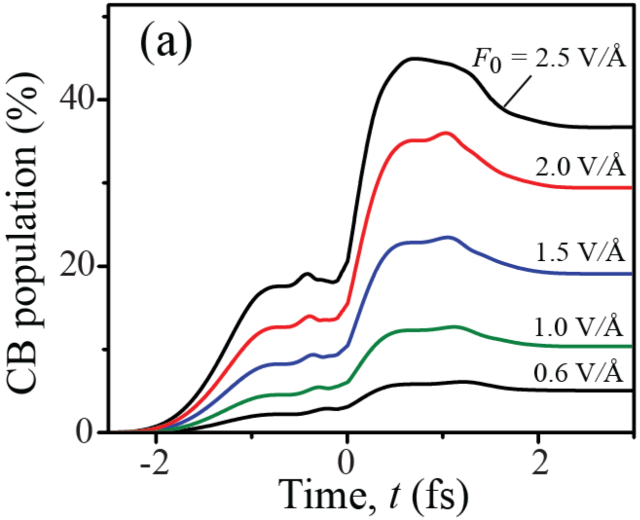


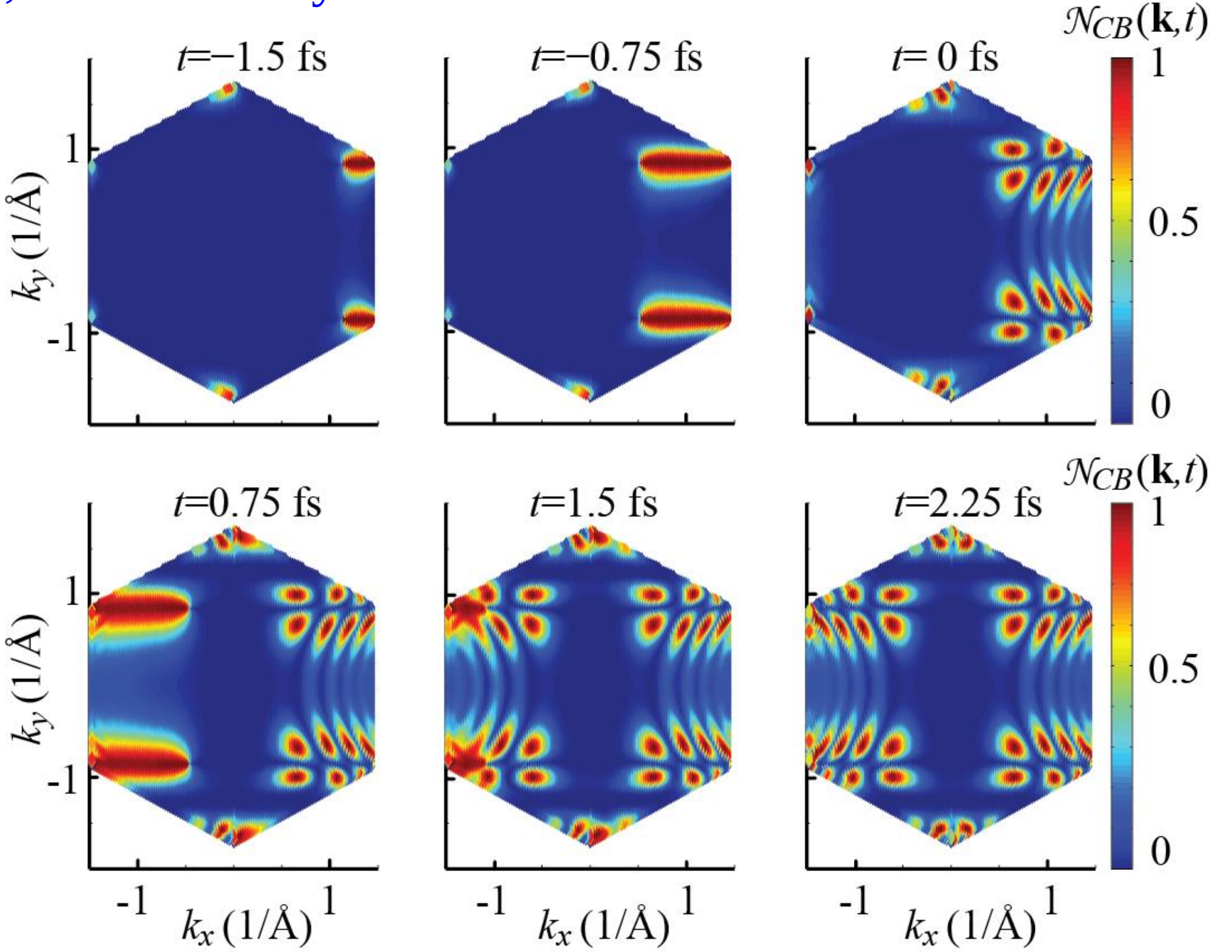




$$\Delta k \sim \frac{\omega}{v_F};\quad \omega \sim 10^{15}\frac{1}{\mathrm{s}},\quad v_F \sim \alpha c \sim 10^{8}\frac{\mathrm{cm}}{\mathrm{s}},\quad \Delta k \sim 10^{7}\frac{1}{\mathrm{cm}} \sim 0.1\frac{1}{Å}$$

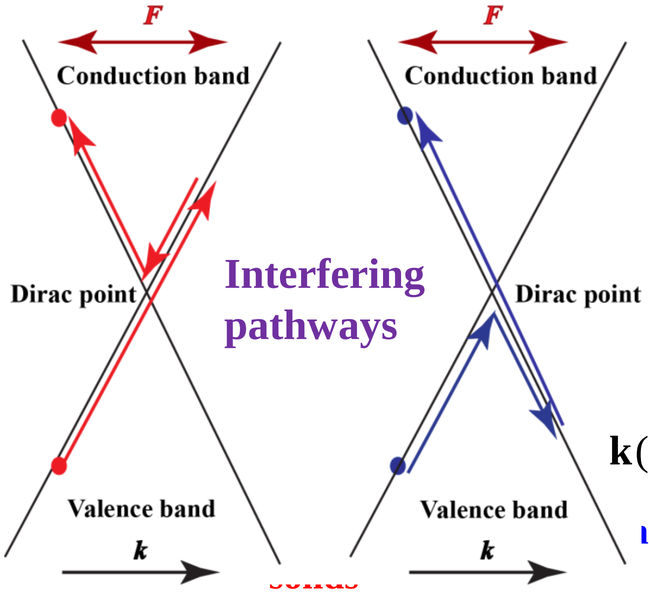
No reversibility, no adiabaticity, interferometry





Dynamics of conduction band population at 2 V/Å

Dirac-point interferometer

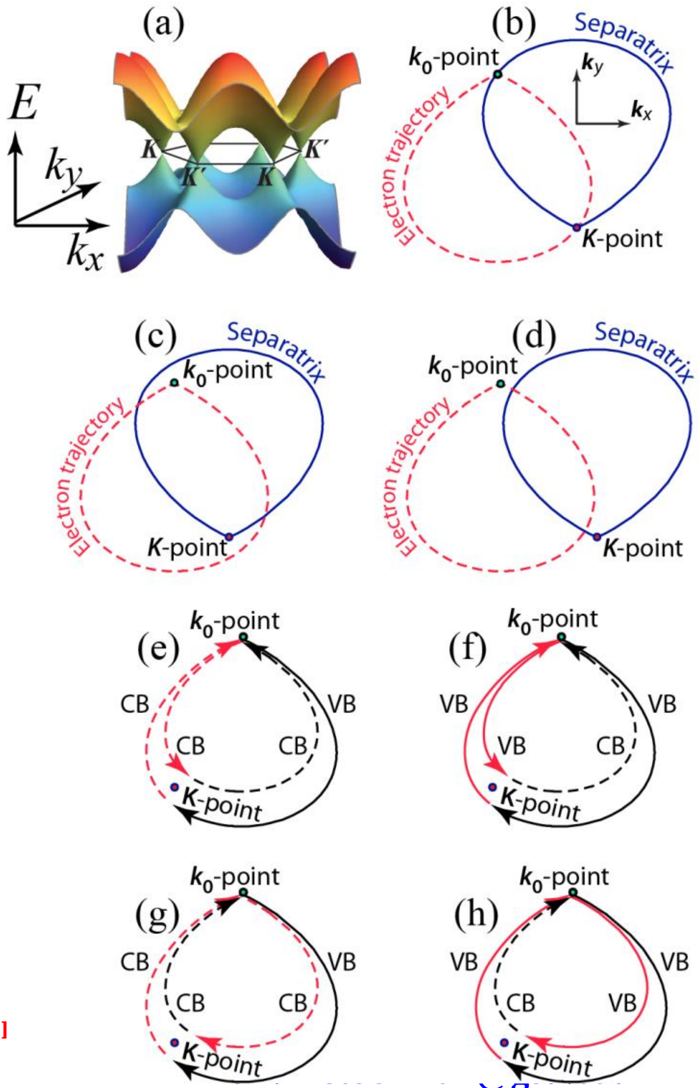


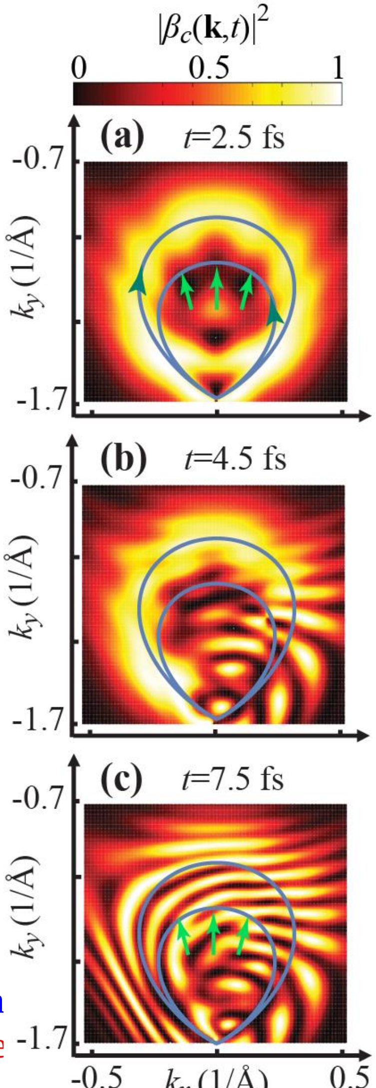
$$\mathbf{k}(t) = \mathbf{k}_0 - \frac{e}{\hbar}\int \mathbf{F}(t)\,dt$$

ttp://www.phy-astr.gsu.edu/stockman
E-mail: mstockman@gsu.edu

H. K. Kelardeh, V. Apalkov, and M. I. Stockman, *Attosecond Strong-Field Interferometry in Graphene: Chirality, Singularity, and Berry Phase*, Phys. Rev. B **93**, 155434-1-7 (2016).

Principles of self-referenced electron interferometry in strong circularly-polarized optical fields





**Attosecond strong-field phenome
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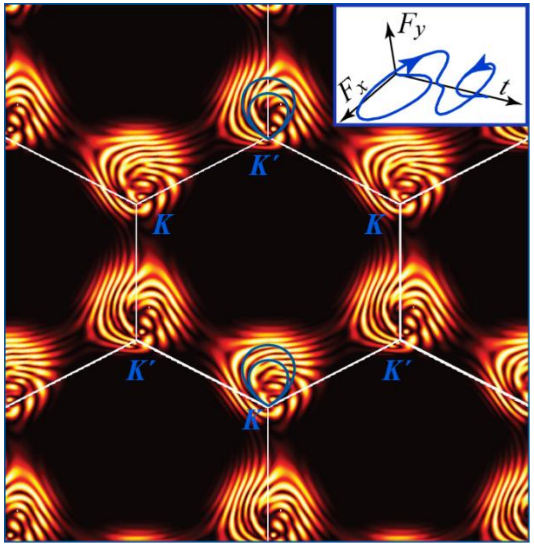
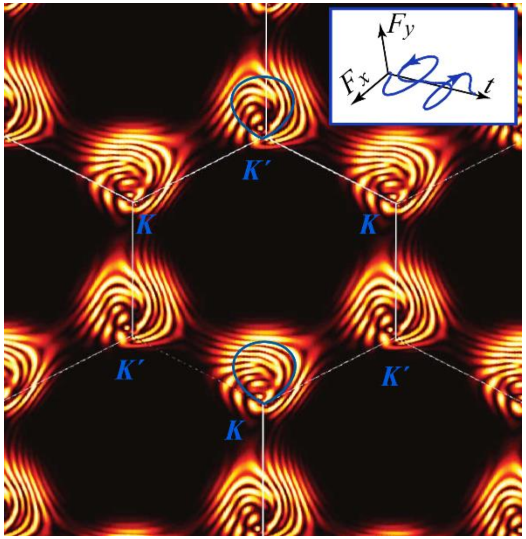
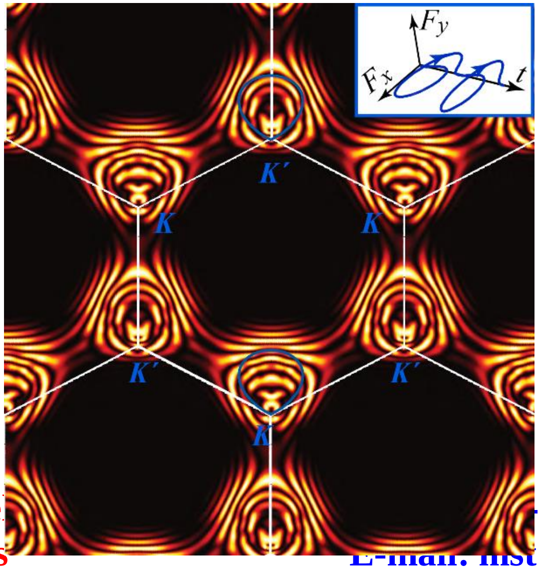
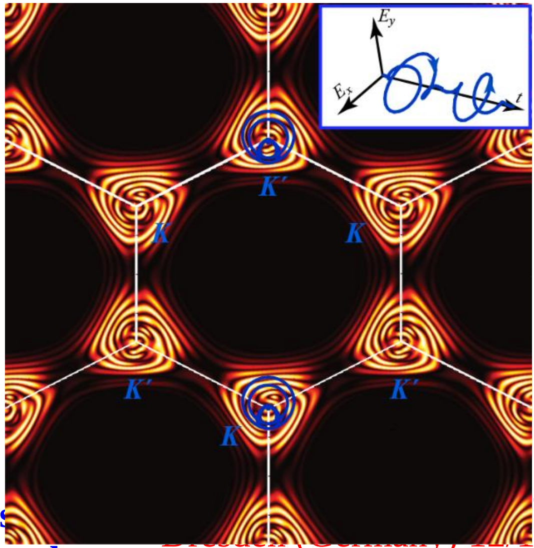
Self-Referenced Electron Interferograms in Graphene Reciprocal Space







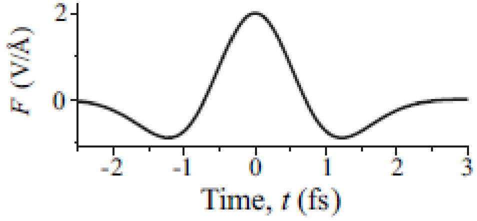


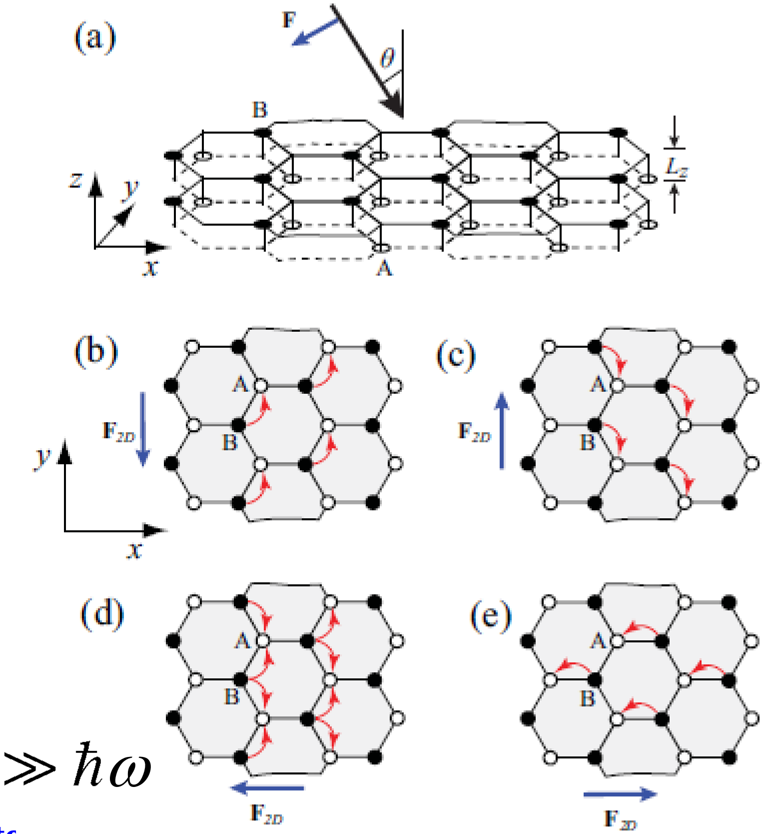
Ultrafast field control of symmetry, reciprocity, and reversibility in buckled graphene-like materials

Phys. Rev. B **92**, 045413-1-9 (2015).

Hamed Koochaki Kelardeh*, Vadym Apalkov†, and Mark I. Stockman‡
Center for Nano-Optics (CeNO) and Department of Physics and Astronomy,
Georgia State University, Atlanta, Georgia 30303, USA

- Silicene: Buckled 2D material
- Two atomic layers, A and are separated vertically by L_z~1 Å.
- Strong vertical field (*z*-component) of a COP-controlled pulse adiabatically shifts electrons toward one of the layers (B in this case)
- Symmetry of the system is reduced from honeycomb to lower, triangular with no center of symmetry
- Silicene in such a field behaves as a field-effect transistor and a diode



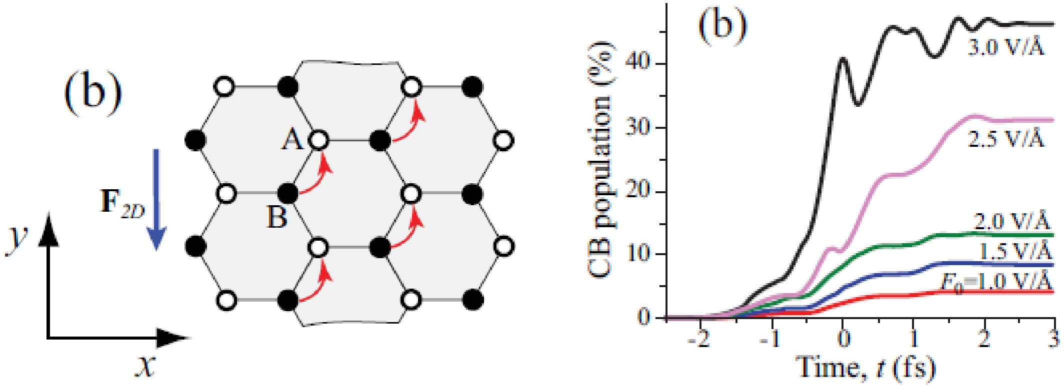


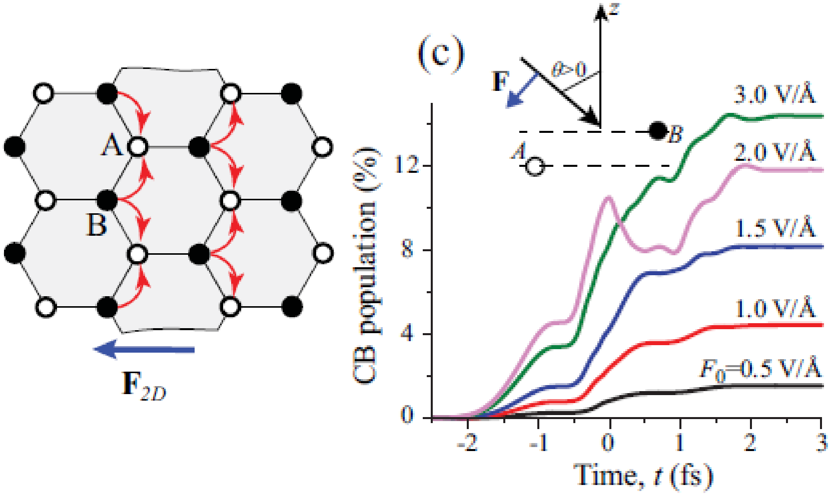
Vertical-direction adiabaticity: $eF_zL_z = \hbar\omega_z \gg \hbar\omega$

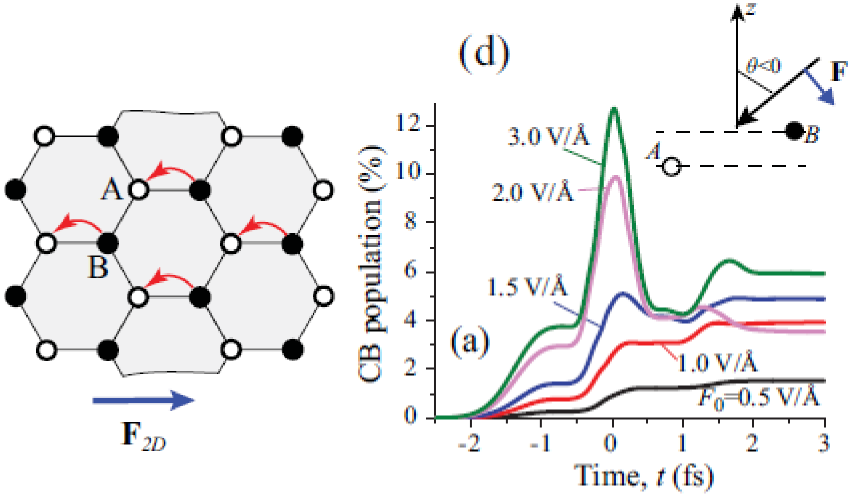
Conduction Band Population: Anisotropic, Non-Reciprocal, Non-Adiabatic (Irreversible or Partly Reversible)

In-plane adiabaticity:

$$eF_{\mathbf{2D}}a \sim \hbar\omega_B \gg \hbar\omega$$







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Strong-Field Resonant Dynamics in Semiconductors

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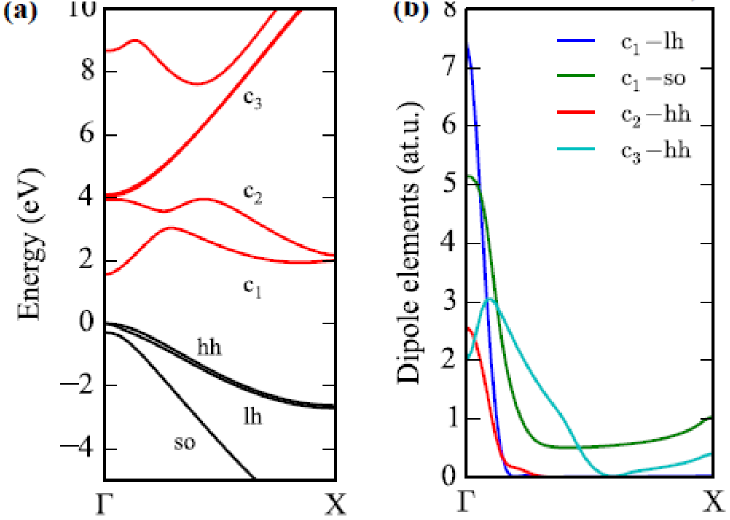
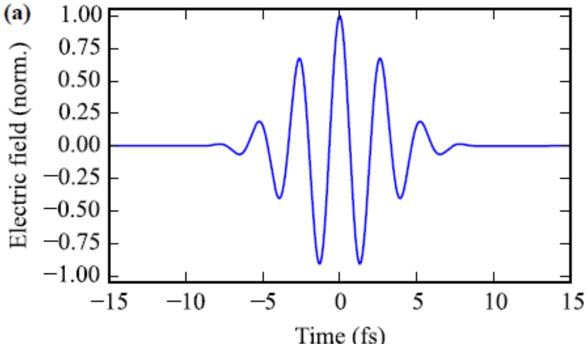
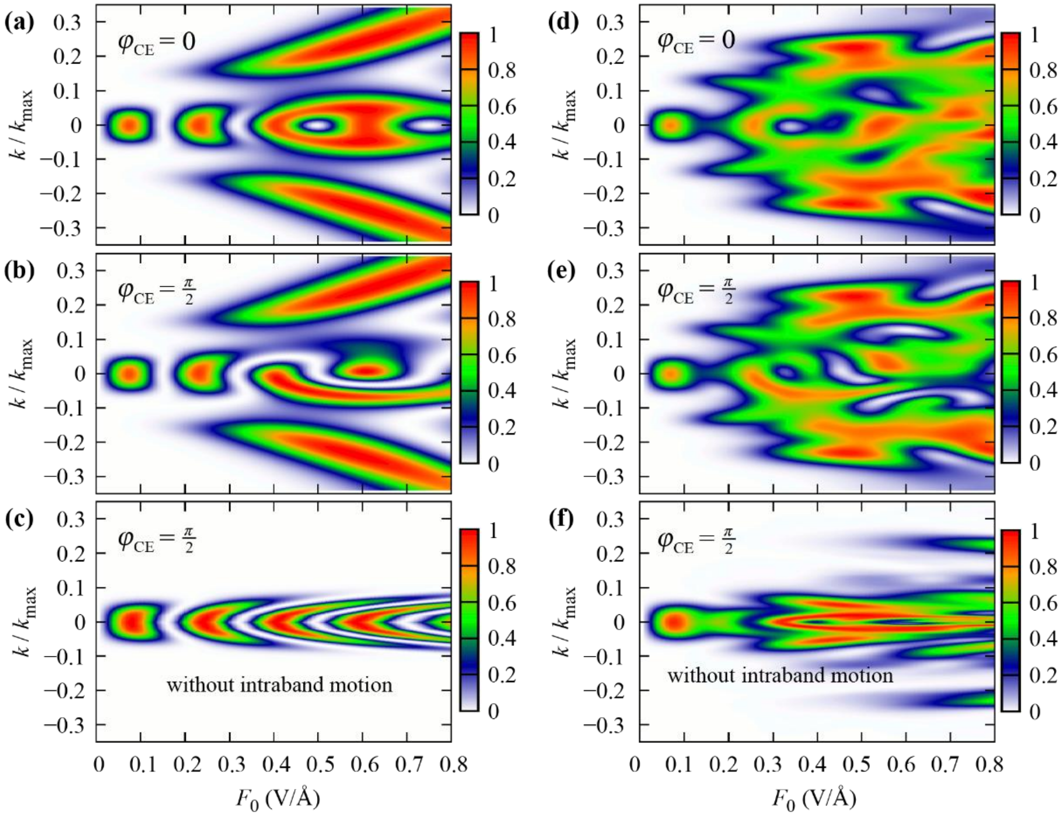


FIG. S1. (a) The energies of three highest valence bands (black) and five lowest conduction bands (red) of GaAs along the line between the Γ and X points. Each of these bands is doubly degenerate. (b) Dipole moments $|d_{ij}(\boldsymbol{k})|$ for the most important interband transitions.



1 CB + 1 VB

3 CB + 3 VB



Residual conduction-band electron population

Kicked Anharmonic Rabi Oscillations (KARO)

Atom Workshop 2016 p.28

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Dresden (Germany) 12/1/2016 12:19 AM

CONCLUSIONS

- Dielectric solids exhibit universal adiabatic behavior in the intermediate range of string optical fields ~2 V/Å.
- Universally, behavior of dielectrics in such fields is similar to (semi)metals with significant optical conductivity and no damage
- Graphene in strong fields behaves non-adiabatically. The electron distribution in the reciprocal space shows self-referenced interferometric fringes related to its topology
- Semiconductors in strong resonant field undergo kicked anharmonic Rabi oscillations (KARO)

Thank you!

Your questions, please