Research in Xu's Group

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Research Areas

- Thermal transport at nanoscale
  - Thermal transport in 2D materials (BP, TI, TE, PV,…), TDTR, Raman
  - Ultrafast dynamics of energy carriers (photons, electrons, phonons, excitons…) – time and frequency domain measurements
  - Radiative transfer at nanoscale (phonon polaritons, meta surfaces, hyperbolic materials,…), ISPI, FTIR…

- Nanoscale optics
  - Field localization using plasmonic nano-sgtructures (optical antenna)
  - HAMR, heat-assisted magnetic recording

- Laser nanomanufacturing
  - Antenna based lithography, heat-guided nanowire growth
  - 3D printing at nanoscale, two-photon, STED, …

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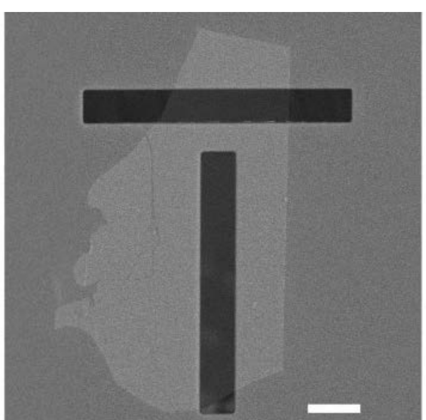
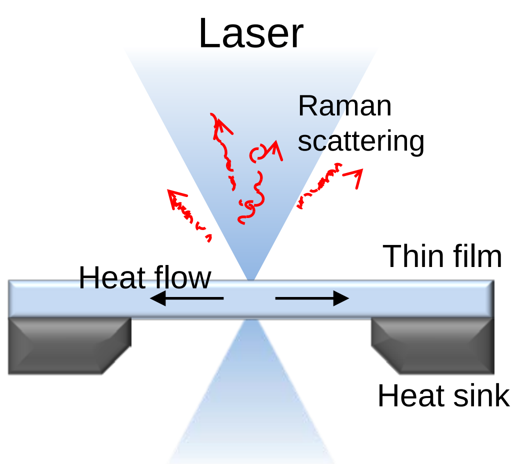
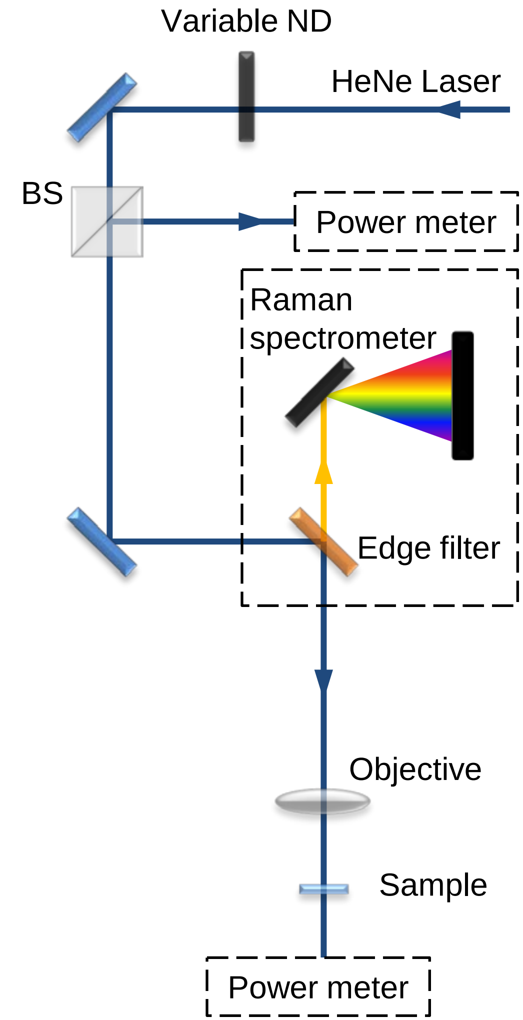
Raman Thermometry for Thermal Transport Studies

- Raman spectrometer: Horiba LabRAM HR800
  - Spectral resolution 0.27 cm^{-1}/pixel
  - Peak fitting uncertainty ~0.02 cm^{-1} (~1 K)
  - 632.8 nm He-Ne laser for Raman excitation and optical heating
- Sample geometry
  - Suspended thin films: in-plane heat transfer
  - As thin as a few nm of films can be studied







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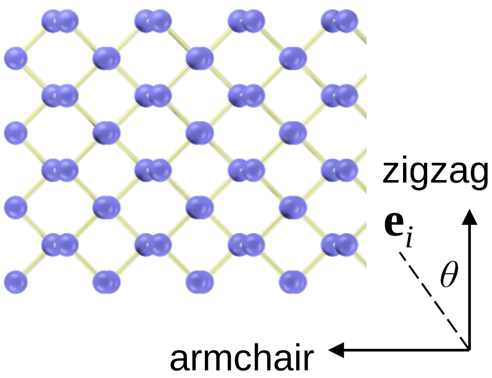
Optical Anisotropy: Polarized Raman Spectroscopy (BP)



- Raman scattering intensity

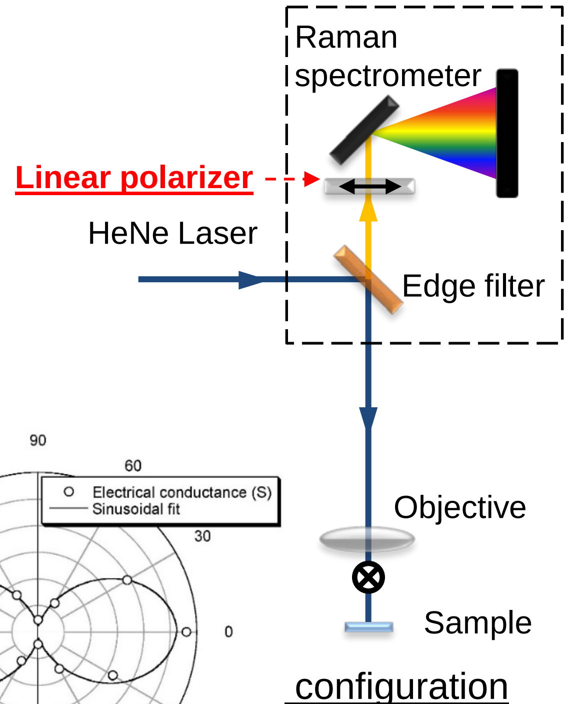
$$I \propto \left|\mathbf{e}_i \times \mathbf{R} \times \mathbf{e}_s\right|^2$$

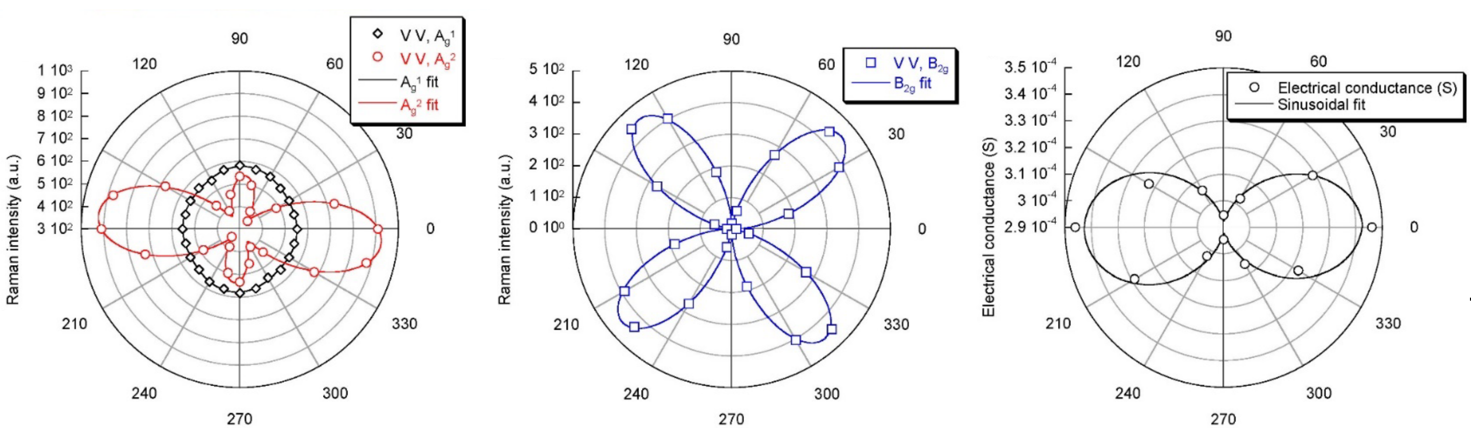
  - Linearly polarized incident laser: $\mathbf{e}_i = (\cos\theta, 0, \sin\theta)$
  - Linearly polarized detection: $\mathbf{e}_s \perp \mathbf{e}_i$ (VH) or $\mathbf{e}_s \parallel \mathbf{e}_i$ (VV)
- Raman tensors of BP

$$\mathbf{R}_{A_g} = \begin{pmatrix} A & & \\ & B & \\ & & C \end{pmatrix}, \quad \mathbf{R}_{B_{2g}} = \begin{pmatrix} & & E \\ & & \\ E & & \end{pmatrix}$$

Raman intensity

$$VH: \begin{cases} I_{A_g} \propto \dfrac{(C-A)^2}{4}\sin^2 2\theta \\ I_{B_{2g}} \propto E^2\cos^2 2\theta \end{cases} \qquad VV: \begin{cases} I_{A_g} \propto \left(A\cos^2\theta + C\sin^2\theta\right)^2 \\ I_{B_{2g}} \propto E^2\sin^2 2\theta \end{cases}$$



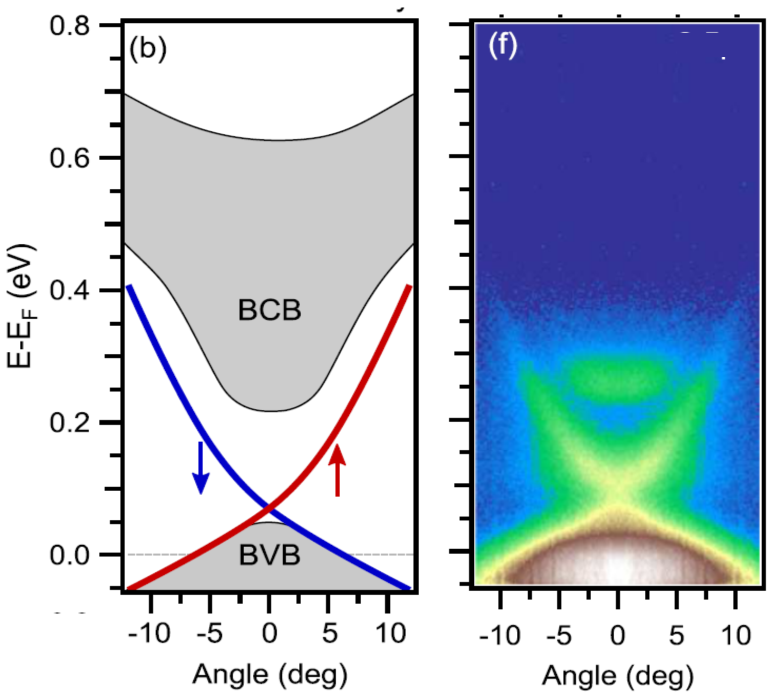


Topological Insulator

Topological insulators (TI)
•Bulk (trivial) states: insulator

Topological surface states (TSS)
•Topological protected metallic states
•Topological transition on its edge (surface for 3-D)
•Spin-momentum locking

We are interested in thermal transport in TI:
- **Surface state contribution to thermal transport**
- **Surface state ultrafast dynamics**
- **Opto-electronic processes and properties and all optical control**



Energy band diagram of Bi_2Se_3
Sobota, et al, *PRL* **2012**.

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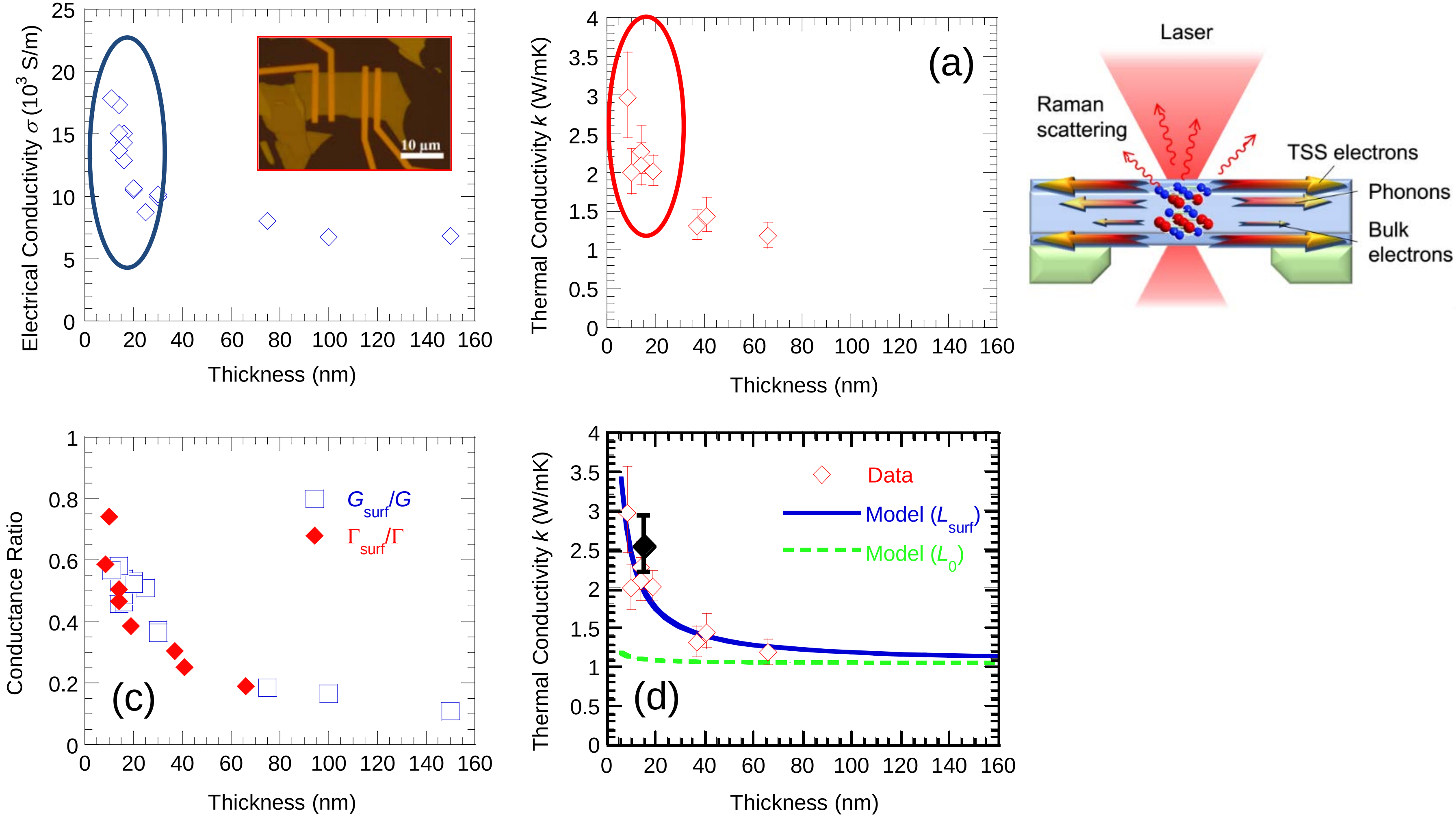
Transport in SS



L_{surf}=4.2 × 10⁻⁷ V²/K²

SS is metallic in terms of transport, can have higher transport capability than metal

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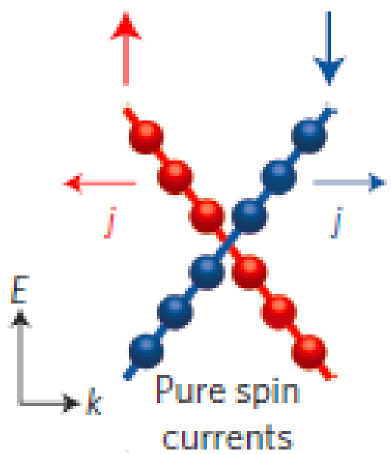
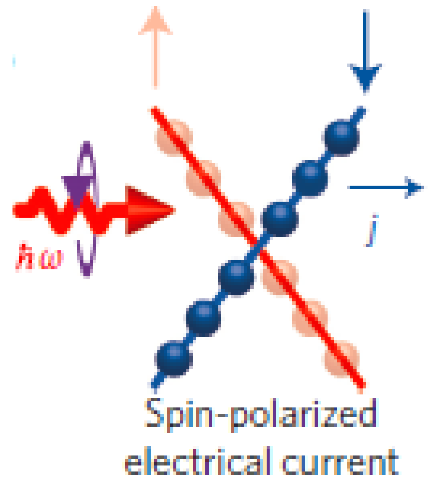
Investigation of Surface State via Optical Excitation (opto-electrical behavior)

- Breaking of inversion symmetry



Dirac cone in equilibrium
McIver et al. Nat. Nanotech 2011

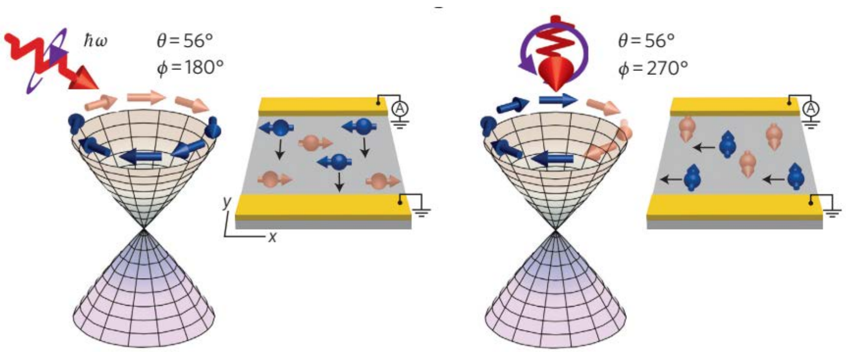


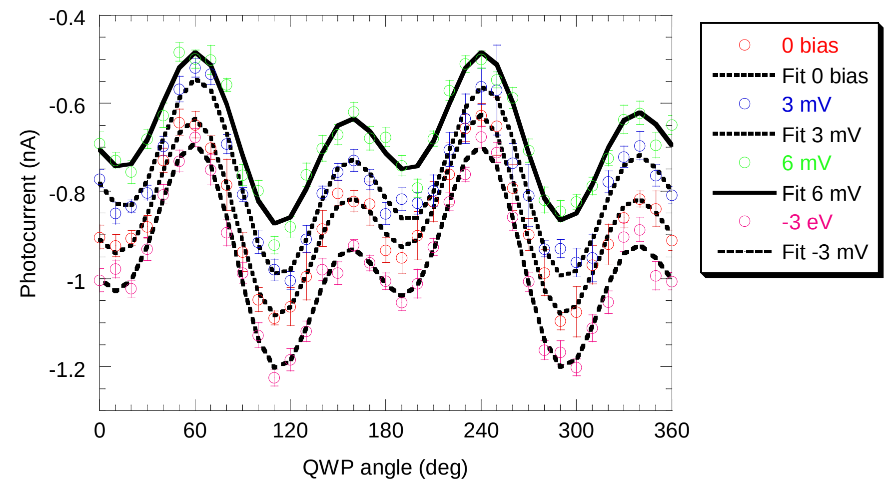
Dirac cone selectively excited by helical photons

- Selection Rule
  - Fermions (electrons) spin - $\pm\frac{1}{2}$
  - Bosons (photons) spin - ± 1

- **Photo induced current**
- Ultrafast dynamics

Photocurrent and SS contribution





- SS current driven by CPL (and hence can be controlled by light)
- SS conductivity can be determined

Ultrafast Dynamics vs. Transport Processes

Measurement of optical response at the ultrafast time scale (~ or < ps), such as optical reflection, transmission, absorption, and non-linear processes vs. wavelength/frequency

Ultrafast laser measurements have become an important tool for investigating thermal transport, in particular at the nanoscale: **fast time scale ~ small length scale for any given transport process**

A typical semiconductor device involves flow of charges (i.e. information) and heat (phonon). The interaction between charge and phonon is of the order of ps. Within 10s of ps changes and phonons are not in equilibrium.

We use ultrafast optical spectroscopy for investigations of ultrafast energy transfer processes in **nanomaterials, electronic devices** and in **energy conversion systems (TE, PV)**.

- **Ultrafast dynamics through probing charge carriers**
- **Ultrafast dynamics through probing phonons**

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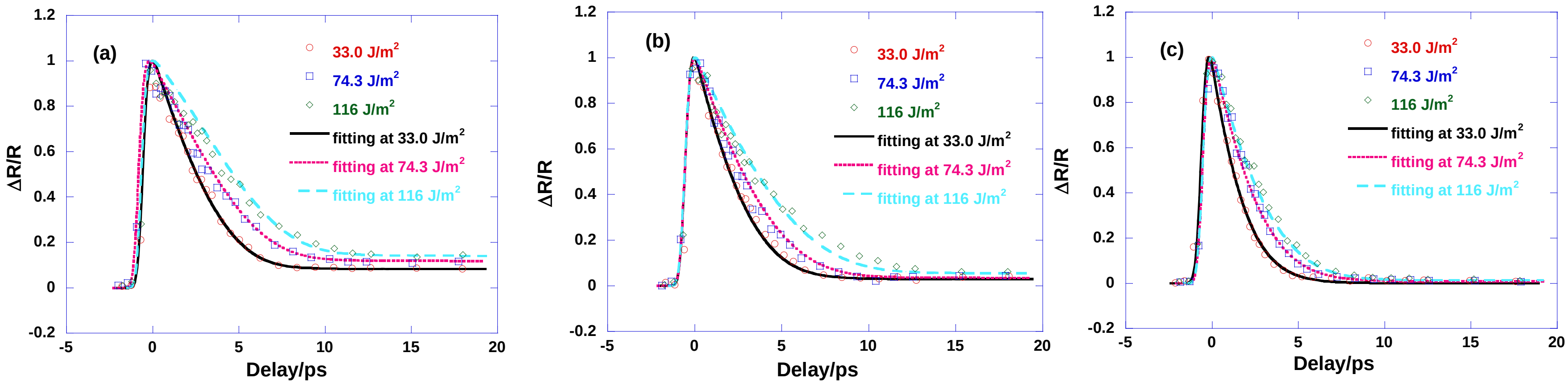
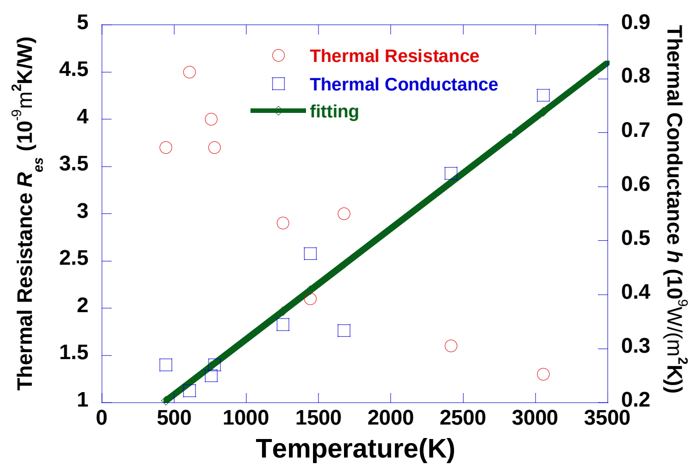
Energy (electron-phonon) Coupling across Interface (interface resistance)

Thin gold films with various thicknesses on silicon



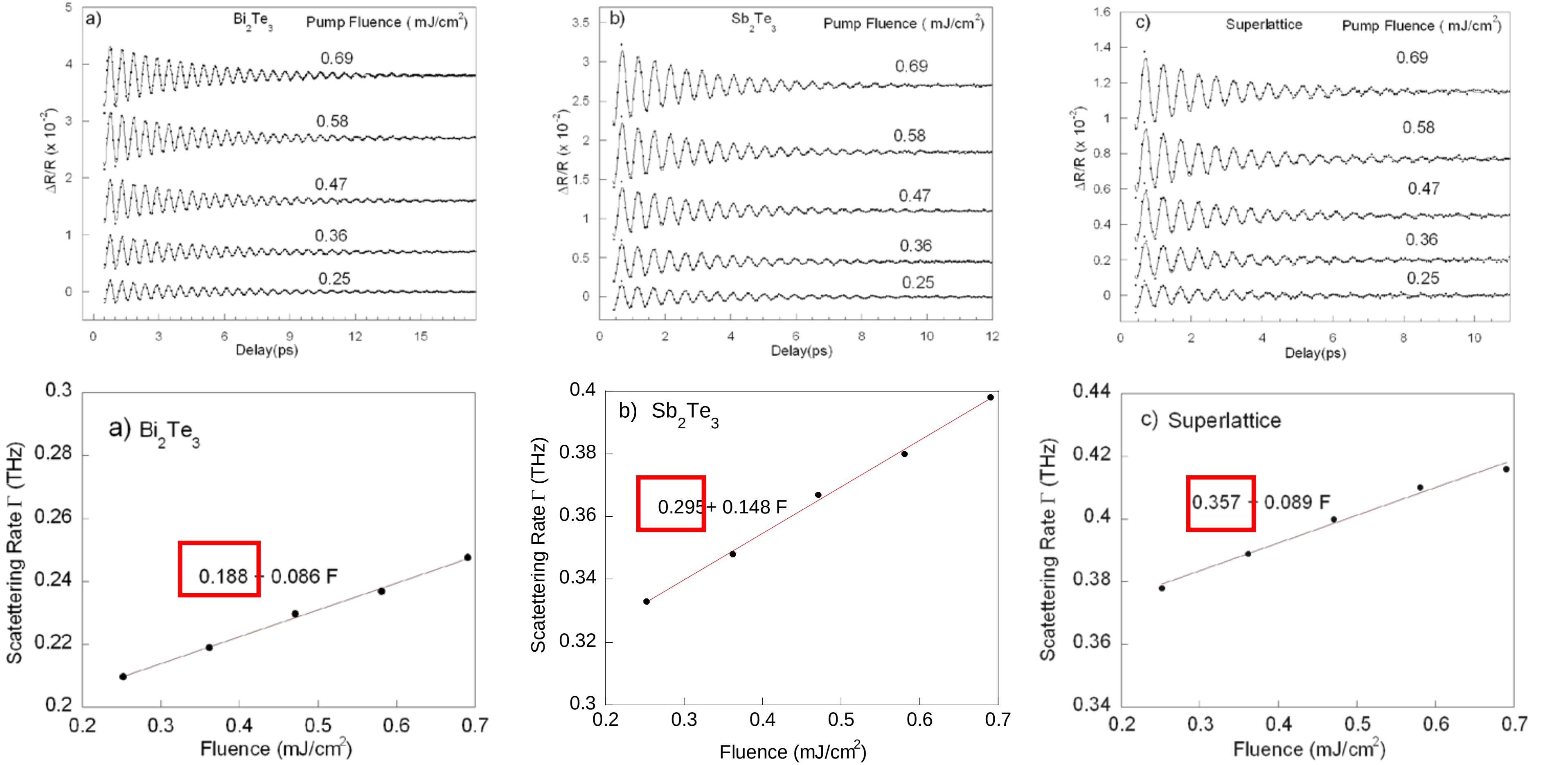
$$G(T) = G_0\left(\frac{A_{ee0}}{B_{ep0}}(T_e + T_l) + 1\right)$$

$$h(T) = h_0\left(C(T_e + T_l) + 1\right)$$



Thermal conductance is a function of temperature

Time-domain Phonon Dynamics
(Bi_2Te_3/Sb_2Te_3 Superlattice)



Excitation of A1g optical phonon mode(s)

Electron – phonon scattering is removed by a fluence dependent study

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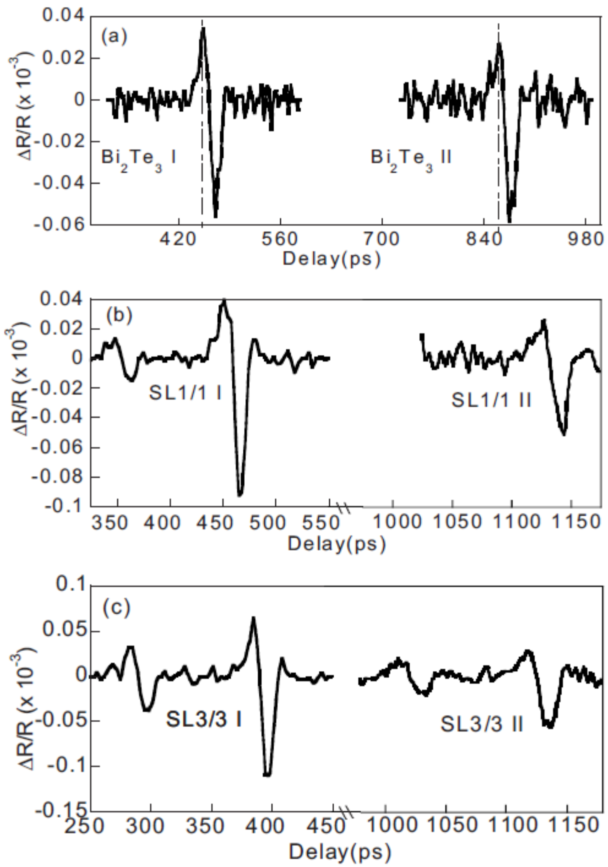
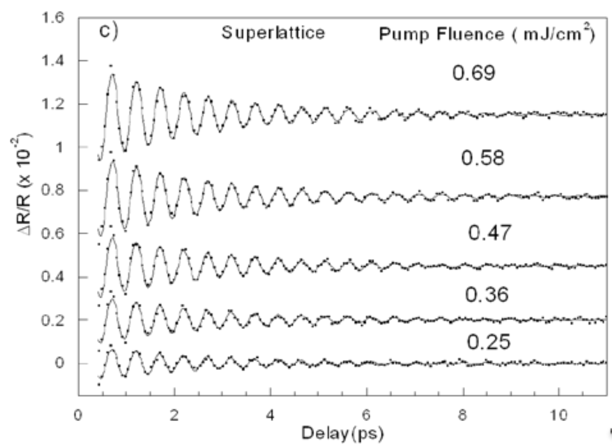
Coherent Ballistic Acoustic Phonon (Bi_2Te_3/Sb_2Te_3 Superlattice)

- Excitation at the surface due to thermoelastic expansion
- Only long wavelength acoustic mode is excited
- Detection of acoustic waves reflected from interfaces



- Phonon scattering at interfaces is much weaker compared with acoustic mis-match model
- Phonon coherence
- For optical phonon, the frequency in superlattice is neither of that of the two constitutive materials



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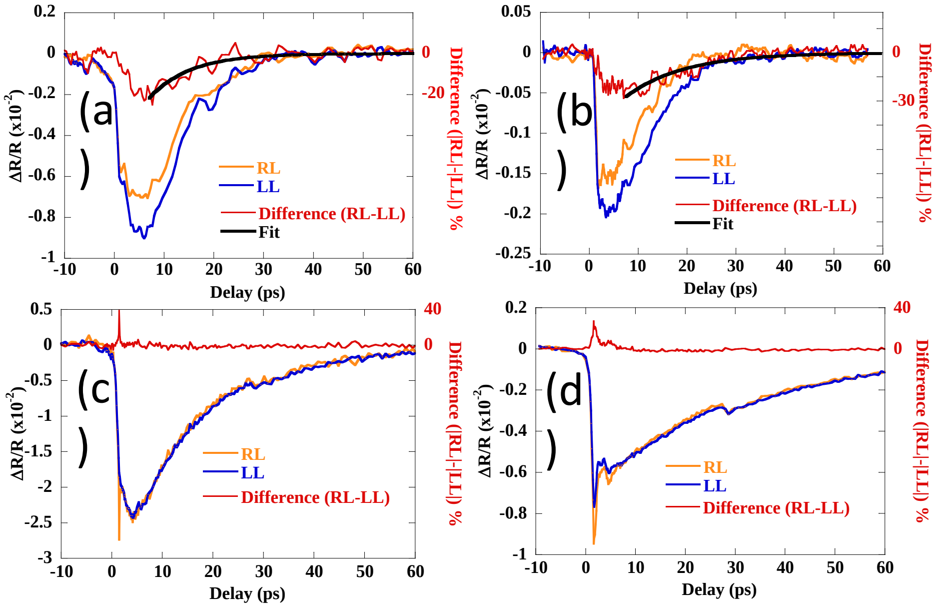
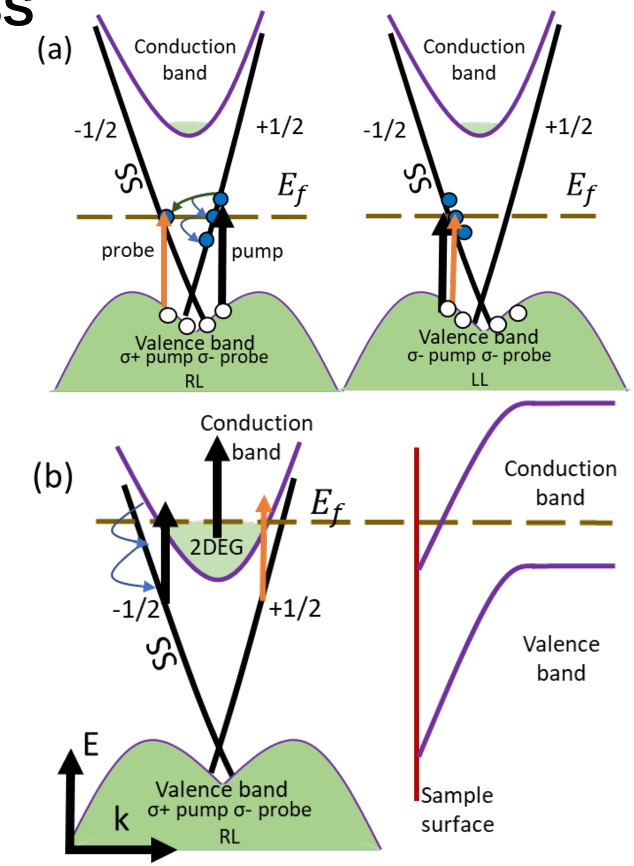
Ultrafast Dynamics of Surface Spin State

- Blow bandgap pump and probe to isolate the SS
- Circular pump and probe to interrogate SS



Helicity dependent dynamics for (a) 14 nm (b) 18 nm (c) 45 nm (d) 75 nm flake with **7 μm pump and 7 μm probe, right or left circularly polarized light**. The difference, i.e. $(|RL|-|LL|)*100/|LL|_{max}$ vs time, can be fit with an exponential decay time $\tau = 8.2$ ps for (a) and $\tau = 12$ ps for (b).



Transition diagram with 7 μm pump and 7 μm probe for (a) thin samples with relatively low Fermi-level. The left figure illustrates σ+ pump and σ- probe (RL), and the right figure σ- pump and σ- probe (LL). LL produces a stronger probe response than RL. (b) Thick samples with high Fermi-level for σ+ pump and σ- probe (RL), which does not produce a helicity dependent signal (see text). The black arrow represents the pump and the orange arrow represents the probe.

- Surface state lasts longer than 10 ps
- Correspondingly the SS diffusion length is longer than micrometers

Iyer et al., PRL 2018

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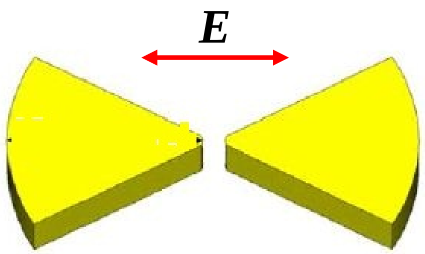
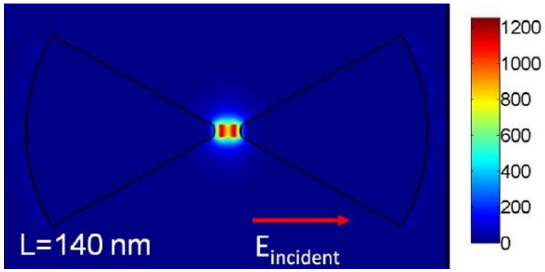
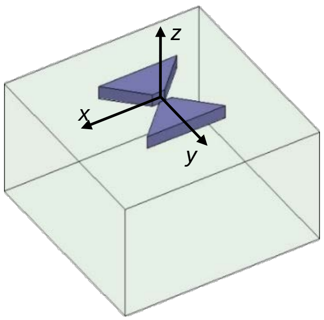
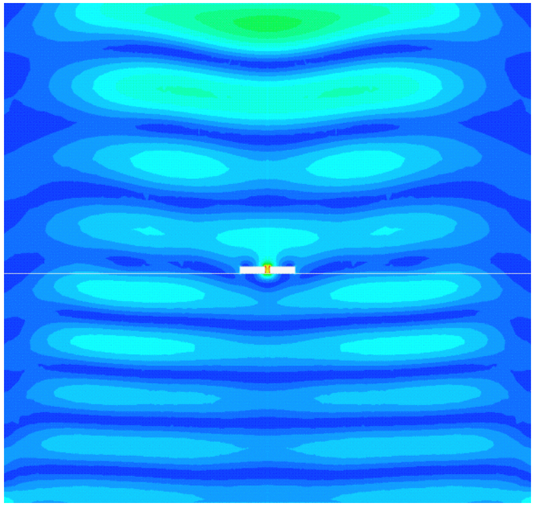
Nanoscale Optics – Optical Antenna



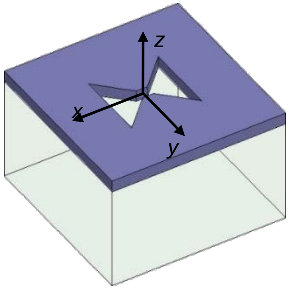


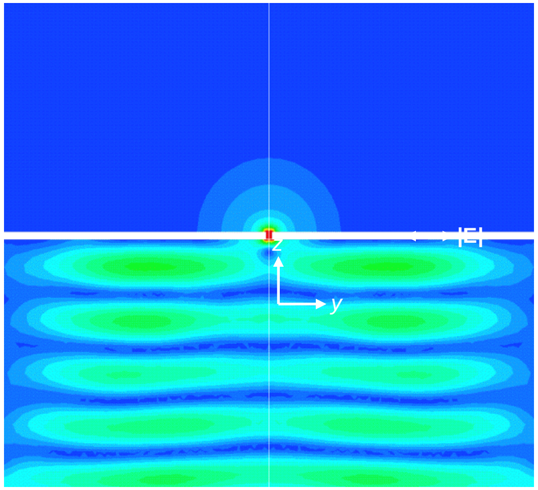
- Enhancing electric field – plasmonic antenna and lighting rod effect
- Enhancement is larger when light is polarized along the tips
- Polarization sensitivity is further enhanced due to the anisotropic optical property in BP





Antenna





Aperture antenna

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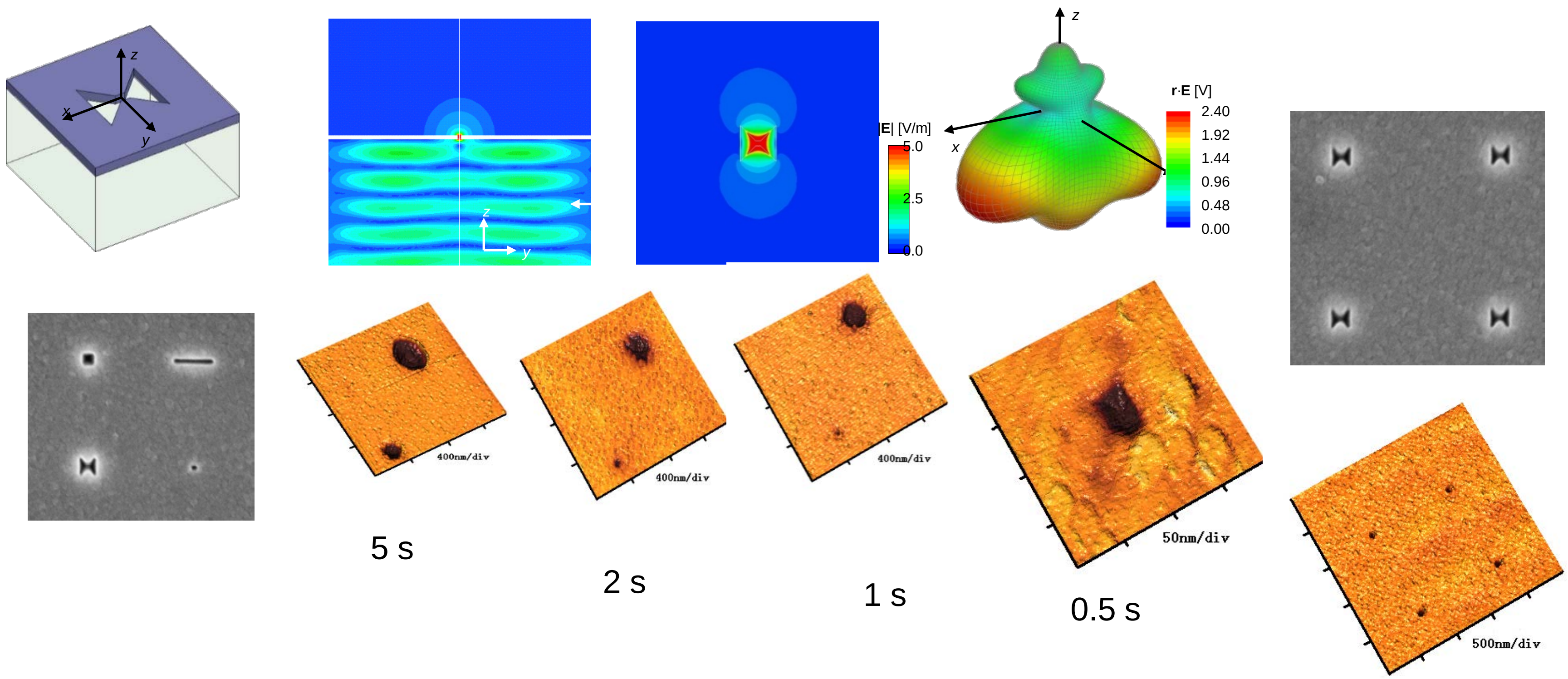
Application: Nanolithography

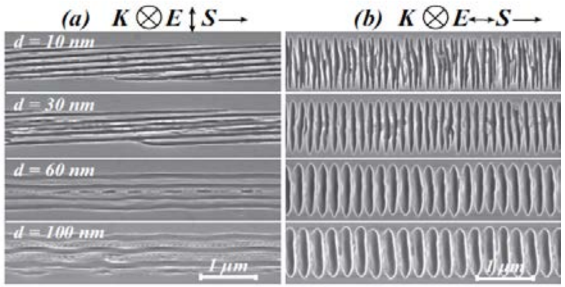
- Near-field nano-optics provides a means to focus light into a nanoscale domain, therefore a light source for nanoscale fabrication

- example, a bowtie shaped aperture “antenna”

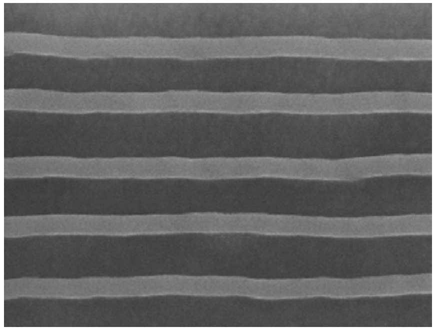


NanoLett, 2006

Achieve sub-Diffraction Limit Dimensions



Laser induced surface periodic structures



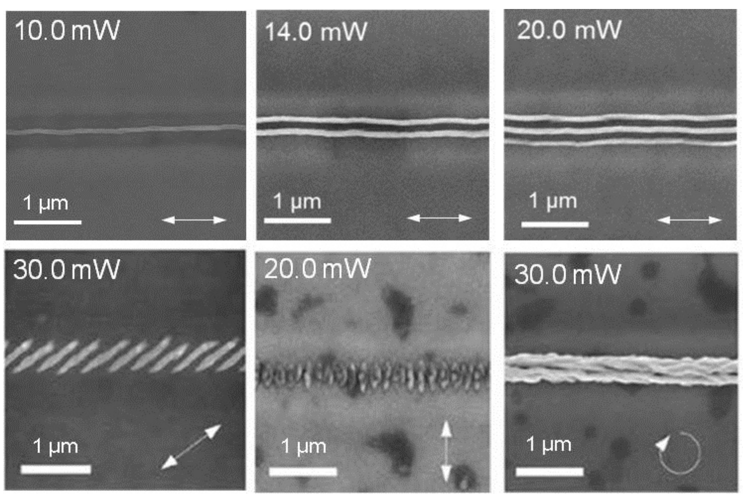
67 nm

69 nm

67 nm

69 nm

66 nm



- Nanowire patterns are formed parallel to the direction of polarization

- FET
- Bio sensor
- p/n diode
- …

Heat-assisted Magnetic Recording

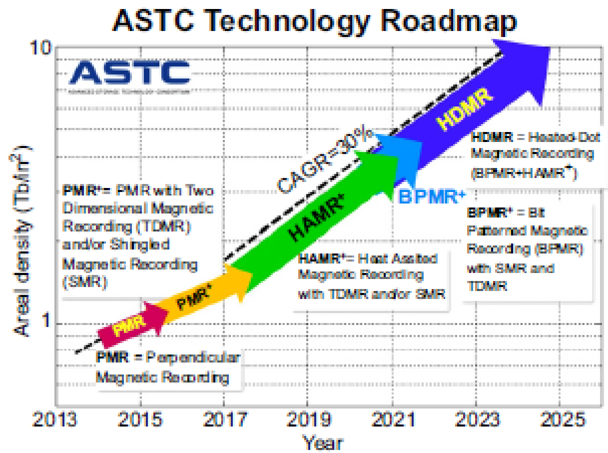
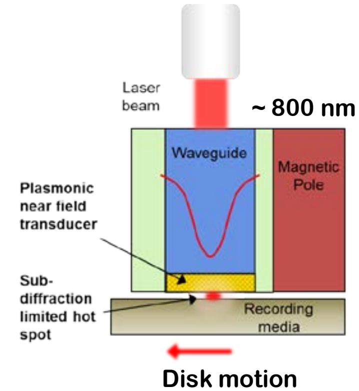


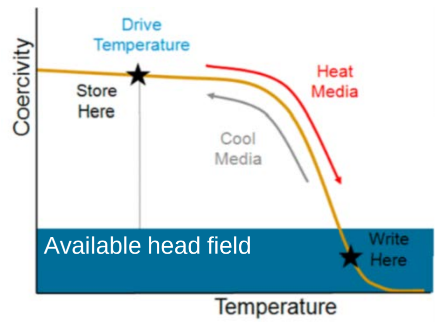
Figure 1. ASTC Technology Roadmap. CAGR: compound annual growth rates.



Heat-assisted magnetic recording (HAMR) **– 1 billion lasers needed per year**

- Areal density: 1 Tb/in^2
- Mark length: 50 nm
- Superparamagnetic limit:

$$\frac{K_u V}{k_B T} \geq 70 \quad V\downarrow, K_u\uparrow, coercivity\uparrow$$



Kryder et al. ***Proc. of the IEEE***

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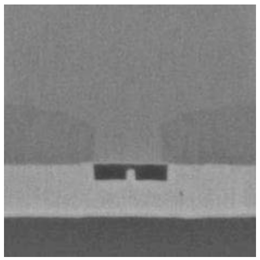
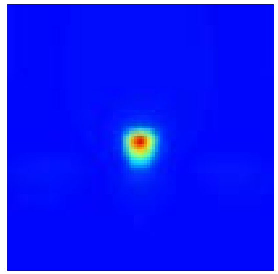
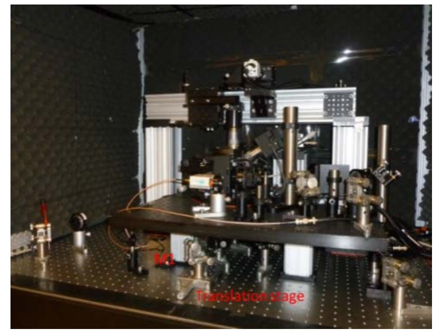
HAMR Demonstration

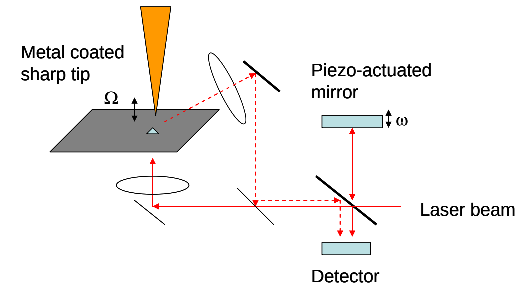


SEM of an NFT (HGST)

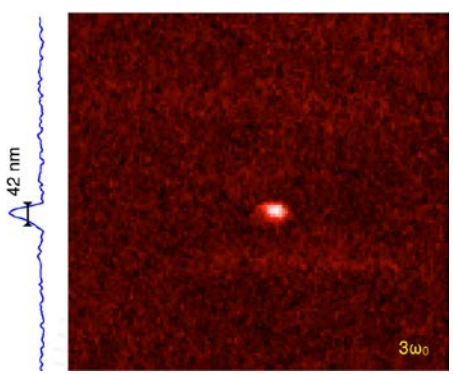


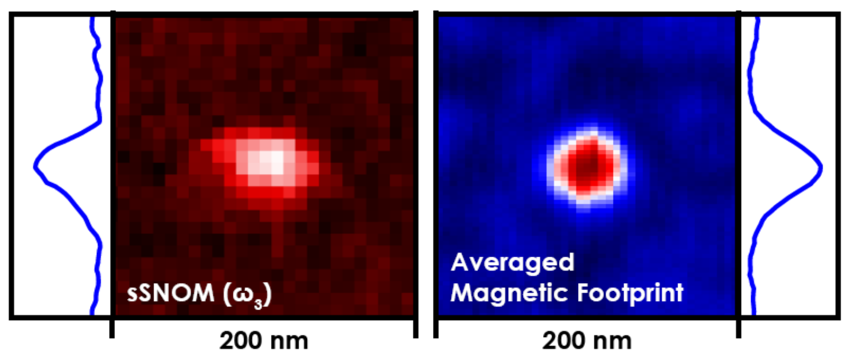
Simulation





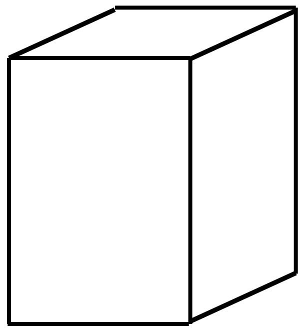
S-NSOM system (~ λ/80 resolution)



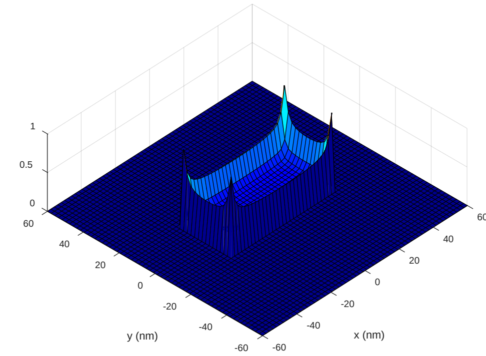


NSOM measurement

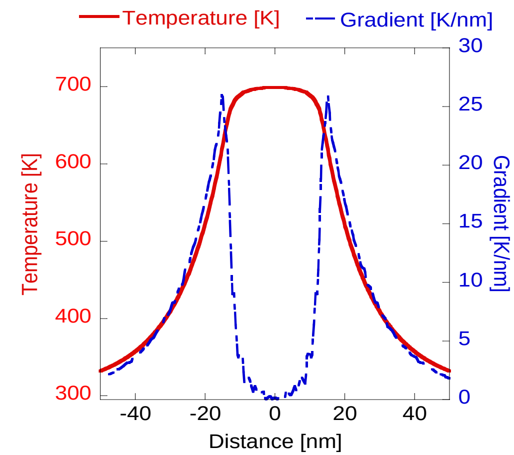
Inverse Design

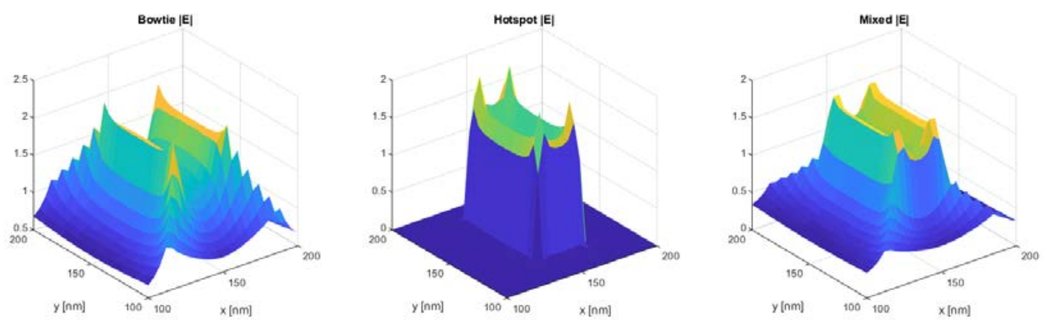


Desired temperature profile

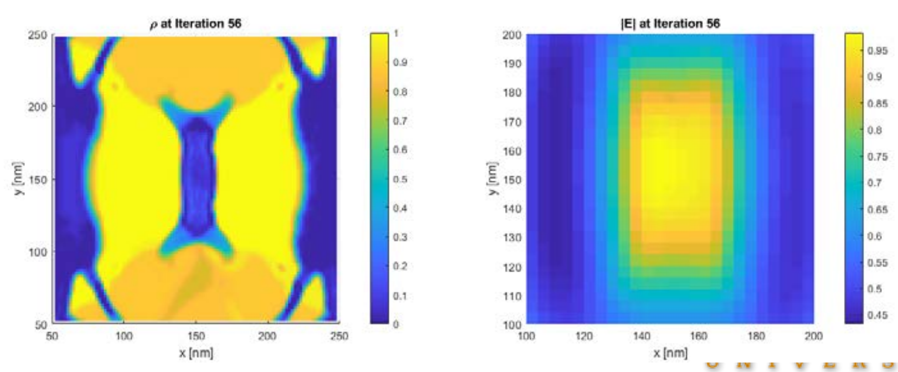


Ideal heat source

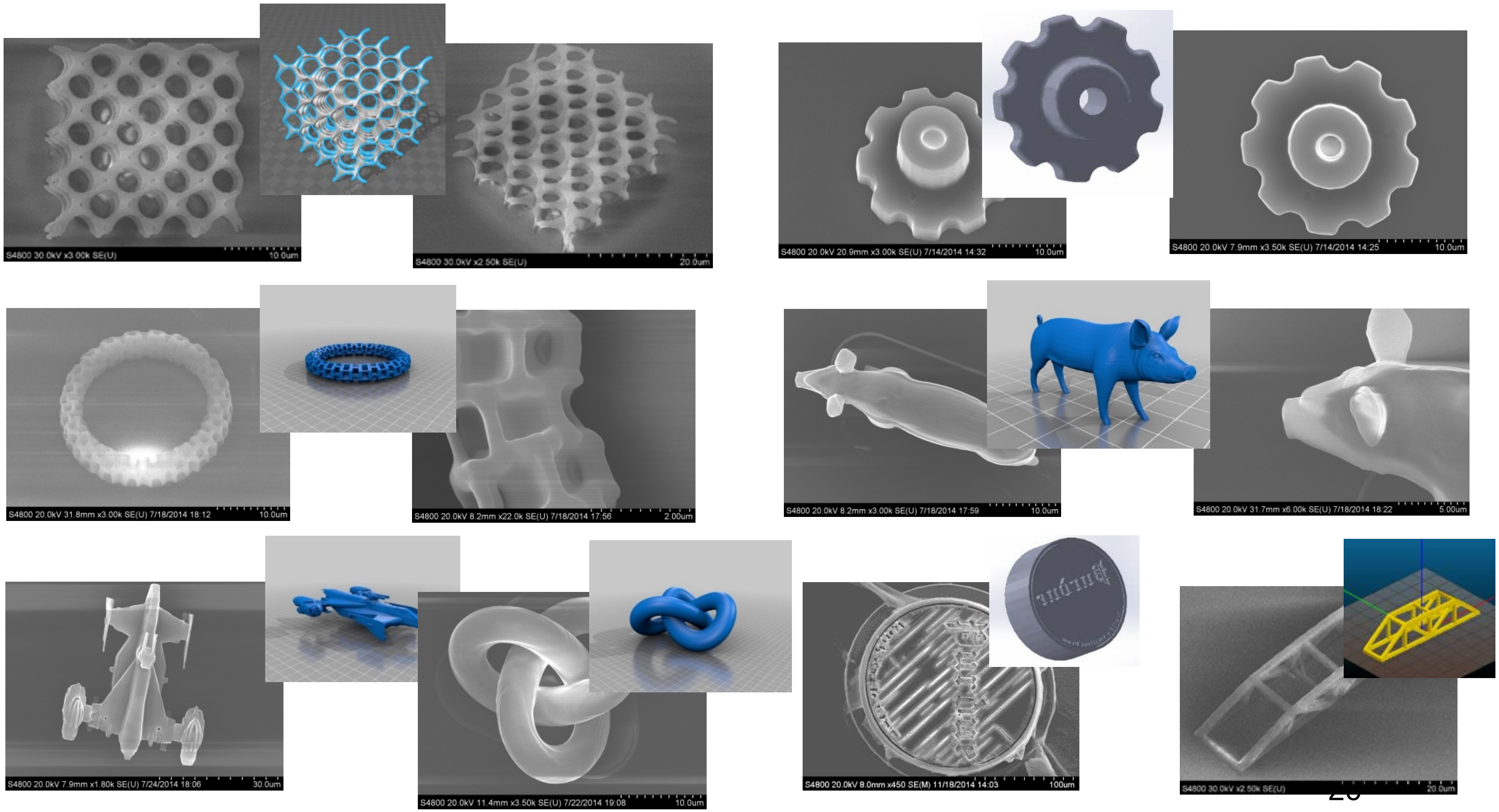




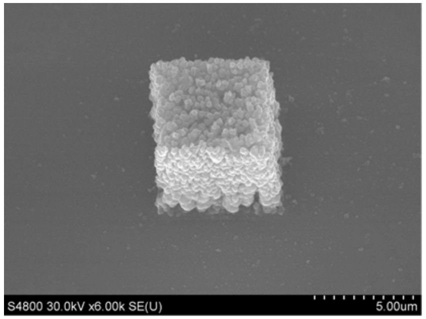
Inverse calculation (not optimization nor MI)

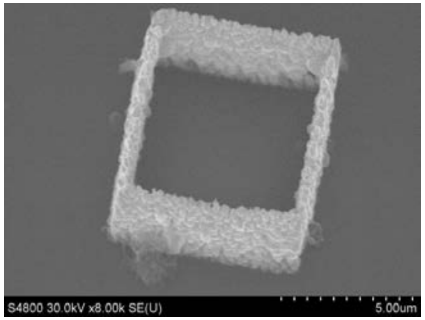


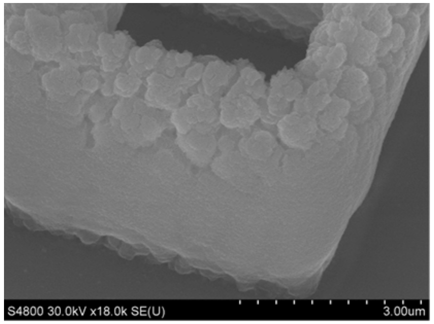
3D Printing with Sub-micrometer Resolution

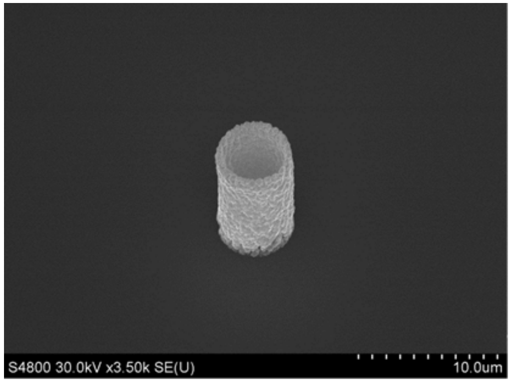


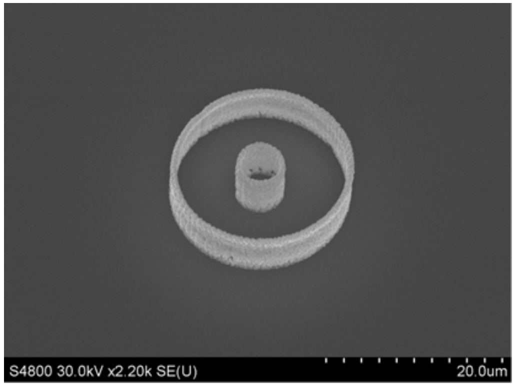
Metallic Structures











Barton et al., 2017, Nanotechnology.

A few other topics:

-Near field radiation
-Magnetic switching – data storage
-Thermoelectrics, TEG, RTG…
-STED lithography and 3D printing

Many Thanks to

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Collaborators

Birck Staff

and

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