QUICK AS A FLASH:
OBSERVING ULTRAFAST LASER-INDUCED
DYNAMICS IN SEMICONDUCTORS

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INTRODUCTION

how does light melt a solid?
photons excite valence electrons...
...and create free electrons...
... causing electronic & structural changes...
... which we measure with another pulse...
structure

Ga  As
INTRODUCTION

structure

bandstructure
INTRODUCTION

structure

bandstructure
INTRODUCTION

structure

bandstructure

dielectric function
INTRODUCTION

structure  bandstructure  dielectric function

Ga  As

\[ E \]

\[ E_1 \]

\[ E(eV) \]

Re \( \varepsilon \)  Im \( \varepsilon \)
structure → bandstructure → dielectric function
INTRODUCTION

structure

bandstructure

dielectric function

70 fs, $10^{16}$ W/m²

$10^{20} - 10^{22}$ cm$^{-3}$
INTRODUCTION

structure  \rightarrow  \text{bandstructure}  \rightarrow  \text{dielectric function}
structure

bandstructure

dielectric function

? → ? → ?

$E$

$L \rightarrow \Gamma \rightarrow X$

$\varepsilon(\omega)$
INTRODUCTION

structure  →  bandstructure  →  dielectric function
INTRODUCTION

structure  ➔  bandstructure  ➔  dielectric function

? ➔  ? ➔  ε

E

k

Γ

X

0  2  4  6

E(eV)
INTRODUCTION

structure

bandstructure

dielectric function

?  

?  

?  

\[
E
\]

\[
\begin{array}{c}
\text{Re } \varepsilon \\
\text{Im } \varepsilon
\end{array}
\]

\[
E (eV)
\]

0  2  4  6
INTRODUCTION

structure  
bandstructure  
dielectric function

?  

\[ E \]

\[ \begin{array}{c}
L \\
\Gamma \\
X
\end{array} \]

\[ E(\text{eV}) \begin{array}{c}
0 \\
2 \\
4 \\
6
\end{array} \]

\[ \text{Re } \varepsilon \\
\text{Im } \varepsilon \]
1 Method
2 Results
3 Discussion
2.2 eV DIELECTRIC CONSTANT

GaAs
(110)
pump
70 fs, 635 nm, 0.2 mJ

2.2 eV DIELECTRIC CONSTANT
2.2 eV DIELECTRIC CONSTANT

probes
350-1100 nm, < 0.1 μJ

all beams
\( p \)-polarized
2.2 eV DIELECTRIC CONSTANT

\[ R \ (58^\circ) \]
\[ R \ (75^\circ) \]

50°
2.2 eV DIELECTRIC CONSTANT

Fresnel equations
2.2 eV DIELECTRIC CONSTANT

Fresnel equations \[ \rightarrow \] Re \( \varepsilon(\omega) \), Im \( \varepsilon(\omega) \)
OUTLINE

1. Method
2. Results
3. Discussion
LOW FLUENCE DATA

-16 ps

GaAs

0.45 $F_{th}$

Dielectric function vs. photon energy (eV)

1.5, 2.5, 3.5, 4.5

0, 10, 20, 30, 40
LOW FLUENCE DATA

0 fs

GaAs

0.45 $F_{th}$

dielectric function

photon energy (eV)
LOW FLUENCE DATA

1 ps

GaAs

0.45 $F_{th}$

dielectric function

photon energy (eV)
LOW FLUENCE DATA

2 ps

GaAs

$0.45 F_{th}$

Dielectric function vs. photon energy (eV)

1.5  2.5  3.5  4.5

Photon energy (eV)
LOW FLUENCE DATA

4 ps

GaAs

0.45 \( F_{th} \)

dielectric function

photon energy (eV)

-10

0

10

20

30

40
MEDIUM FLUENCE DATA

![Graph showing dielectric function vs. photon energy for GaAs at 0 fs and 0.70 *F_th.](image)
MEDIUM FLUENCE DATA

250 fs

GaAs

0.70 $F_{th}$

dielectric function

photon energy (eV)
MEDIUM FLUENCE DATA

1 ps

GaAs

0.70 $F_{th}$

Dielectric function vs. photon energy (eV)

-10
0
10
20
30
40

1.5
2.5
3.5
4.5

Photon energy (eV)
MEDIUM FLUENCE DATA

2 ps

GaAs

0.70 \frac{E}{E_{th}}

dielectric function

photon energy (eV)

-10

0

10

20

30

40
MEDIUM FLUENCE DATA

4 ps

GaAs

0.70 \( \frac{F}{F_{th}} \)

a-GaAs

dielectric function

photon energy (eV)
HIGH FLUENCE DATA

0 fs

GaAs

1.6 $F_{th}$

Dielectric function vs. photon energy (eV) for GaAs at 0 fs.
HIGH FLUENCE DATA

250 fs

GaAs

1.6 $F_{th}$

dielectric function

photon energy (eV)
HIGH FLUENCE DATA

500 fs

GaAs

1.6 \frac{F}{F_{th}}

Dielectric function vs. photon energy (eV) for GaAs at 500 fs.
HIGH FLUENCE DATA

4 ps

GaAs

Dielectric function vs. photon energy (eV) for GaAs at 4 ps, showing a marked decrease at 1.6 $F_{th}$. The graph illustrates the change in dielectric function with photon energy, highlighting the material's response under high fluence conditions.
CARRIER DENSITY

\[ \tau = 0.15 \text{ fs} \]

- Plasma frequency (eV)
- Time delay (ps)

1.6 \( \varepsilon_{th} \)
CARRIER DENSITY

![Graph showing the relationship between plasma frequency (eV) and time delay (ps). The graph includes two curves, one labeled $2.1 F_{th}$ and the other $1.6 F_{th}$. The time delay is 0.15 fs.]
CARRIER DENSITY

![Graph showing plasma frequency vs. time delay](image)

- Plasma frequency (eV)
- Time delay (ps)
- \(\tau = 0.15\) fs

Lines represent different carrier densities:
- \(1.3 F_{th}\)
- \(1.6 F_{th}\)
- \(2.1 F_{th}\)
Carrier Density

Graph showing the plasma frequency (eV) vs. time delay (ps) with different symbols and lines for various carrier density levels. The graph includes labels for 1.2 $F_{th}$, 0.9 $F_{th}$, 1.3 $F_{th}$, 1.6 $F_{th}$, and 2.1 $F_{th}$, with $\tau = 0.15$ fs.
OUTLINE

1. Method
2. Results
3. Discussion
LOW FLUENCE DATA

0 fs

GaAs

0.45 $F_{th}$

dielectric function vs. photon energy (eV)
DISCUSSION

structure  

bandstructure  

dielectric function

GaAs

Re ε

Im ε

$E (eV)$
SHORT TIME SCALE (≈0.5 ps)

structure

bandstructure

dielectric function
SHORT TIME SCALE (≈0.5 ps)
SHORT TIME SCALE (≈0.5 ps)

structure

bandstructure

dielectric function

Ga

As

E

E

E(\text{eV})
SHORT TIME SCALE (≈0.5 ps)

structure

bandstructure

dielectric function
**SHORT TIME SCALE** ($\approx 0.5$ ps)

- Structure
- Bandstructure
- Dielectric function

(Graphical representations of structures and data analysis)
SHORT TIME SCALE (≈0.5 ps)

structure

bandstructure

dielectric function

SHORT TIME SCALE ($\approx 0.5$ ps)

- electronic effects dominate at short time scales...
...but they are not as simple as we used to think
LOW FLUENCE, LONG TIME SCALE

structure

bandstructure

dielectric function
carrier density down, electronic effects subsided...
...and lattice heats due to carrier relaxation
LOW FLUENCE, LONG TIME SCALE

structure

bandstructure

dielectric function

...and lattice heats due to carrier relaxation
gradual drop in gap → not electronic effect
HIGH FLUENCE, LONG TIME SCALE

structure

bandstructure

dielectric function

Ga
As

CB
VB

$E$
BROADBAND DATA

fluence (kJ/m²)

reversible  1.0  irreversible

EXCITATION
BROADBAND DATA

fluence (kJ/m²)

reversible  1.0  irreversible

EXCITATION

electronic effects

time (ps)

10
1
10
0.1
BROADBAND DATA

fluence (kJ/m²)

reversible 1.0 irreversible

time (ps)

0.1
1
10

EXCITATION

electronic effects:
bandstructure change
BROADBAND DATA

fluence (kJ/m²)

reversible  1.0  irreversible

EXCITATION

electronic effects:
bandstructure change  bandgap collapse

time (ps)

10  1  0.1
BROADBAND DATA

fluence (kJ/m²)

reversible 1.0 irreversible

time (ps)

0.1

0.1

0.1

0.1

EXCITATION

electronic effects:

bandstructure change

bandgap collapse

hot lattice
**BROADBAND DATA**

Fluence (kJ/m^2)

Reversible 1.0 Irreversible

Time (ps)

0.1 1 10

Excitation

Electronic effects:
- Band structure change
- Bandgap collapse

- Hot lattice
- Disordered lattice
- Metallic $\varepsilon(\omega)$
- measurement of $\varepsilon(\omega)$ identifies ultrafast phase changes

- initial response is electronic, via band structure and electron occupation changes

- structural effects dominate after a few ps

- interesting reversible regime
CONCLUSIONS

- strong electronic excitation can drive a structural transition

- femtosecond lasers allow us to see the dynamics of the transition
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http://mazur-www.harvard.edu