



Aron @ Columbia

The “early” years



Cyrus F. Hirjibehedin

MIT Lincoln Laboratory

Irene Dujovne

University of Massachusetts Amherst

Rui He

Texas Tech University

Columbia University

- Aron and Horst “moved” from Bell Labs to Columbia University in 1998
- We are the first of his graduate students at Columbia University:
 - Cyrus Hirjibehedin
 - Irene Dujovne
 - Rui He
 - Jun Yan
 - Trevor Rhone
 - Sheng Wang
 - Antonio Levy
 - Ziyu Liu
- There were also post-docs and many undergraduate and visiting students

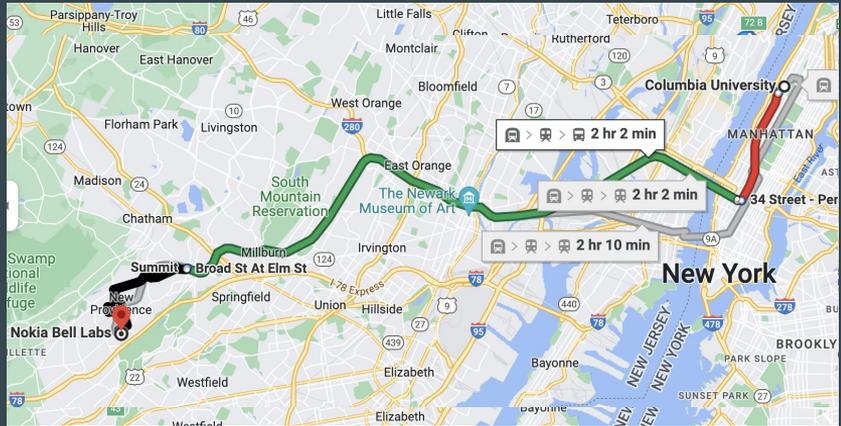
Apologies if we are missing someone



Bell Labs, Murray Hill, NJ



Photo by John Gates courtesy UCSC



Courtesy Google Maps



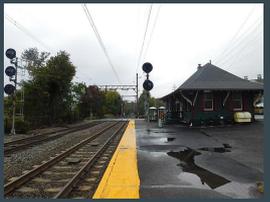
116th Street Station



Penn Station



Summit Station



Murray Hill Station

The privilege of working at Bell Labs



- Never-ending hallways of research labs with world-class research staff who were very friendly to graduate students
- Stimulating lunchtime conversations with people from across the lab
- Lively discussions at seminars

Bell Labs Pictorial Directory



PINCZUK, A. 11311
Aron



PINCZUK, A. 11134
Aron MH 5429
charm!lap

E
Fe



ENGLER, D. 11136
Dan MH 7297



EISENSTEIN, G. 11281
Gus MO 7211



EISENSTEIN, J. 11154
Jim MH 6983
charm!je



ENGINGER, J. 11118
Tony MH 3143
physicists



ELROD, G.W. 11227
Gary MH 3373
alice!ge



ELLINGTON, M.B. 11521
Myra MH 5463
samwiselmb



ELLIOTT, R.J. 11276
Ruby-Jane MH 2819
resarch!je



ELSER, V. 11111
Vee MH 6383
physicsvet



ENG, K.Y. 11343
Kar MO 2361
vac!35!ke



ENGLISH, J.K. 11152
Jane MH 7463



ENOS, J.R. 11354
Bob MO 2919
vac!33!je



EPWORTH, R.W. 11315
R.W. MO 5338
Roper



ERNST, E. 11151
Evely MO 3658
samwiselere



ESPINOSA, G. 11112
Jerry MO 2266



EZZAV, A.K. 11383
Howard MO 2068
allegra!ke



FALSETANO, R.L. 77917
Robin MO 7702
allegra!if



FARRELL, B. 11223
Bob MO 3520



FAROOK, R.C. 11576
Roger MO 6214
samwisestuffin



FASTNACHT, R.A. 11523
Ron MO 4269



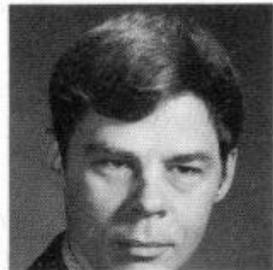
FEDOROVICH, G. 11525
Garry MO 3922
samwiselgery



STORMER, H.L. 11154
Horst



STORMER, H. 11134
Horst MH 3380



PFEIFFER, L. 11134
Loren



EISENSTEIN, J. 11154
Jim MH 6983
charm!je

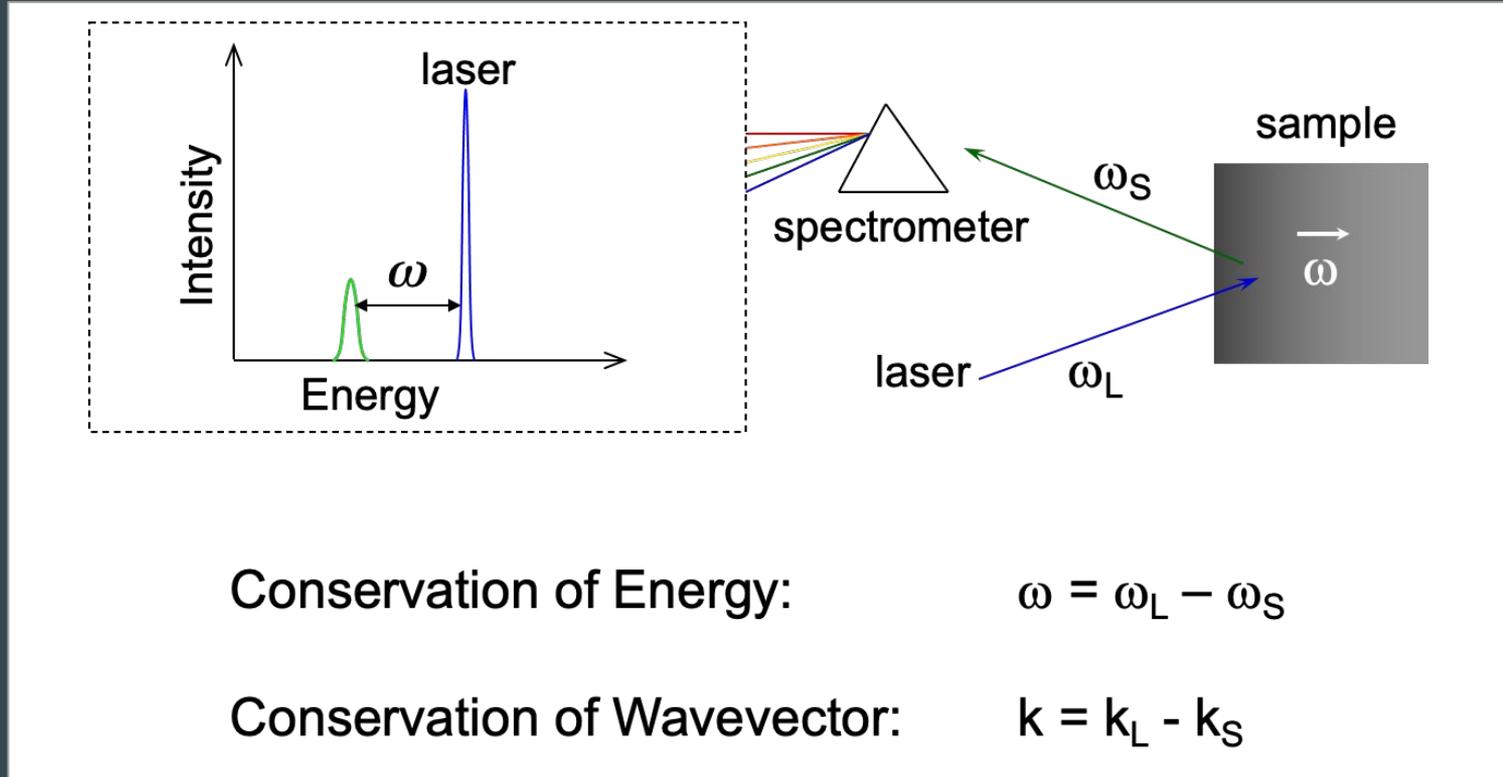


PLATZMAN, P.M. 11115
Phil



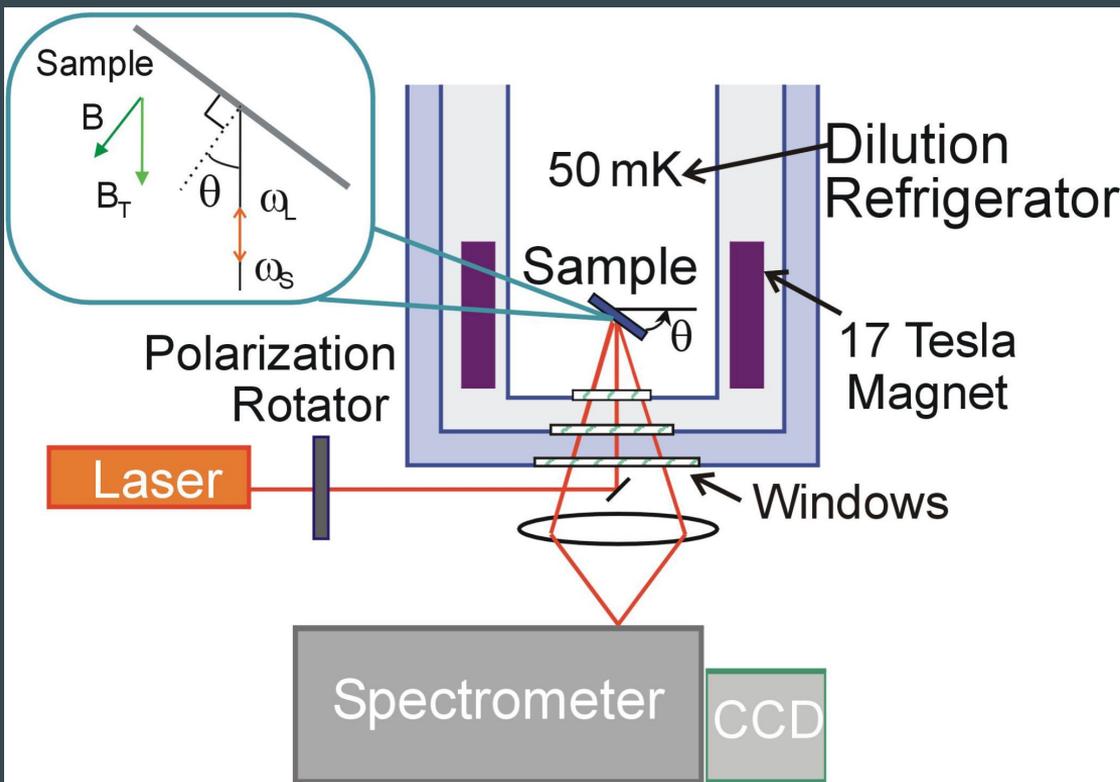
CAPASSO, F. 11155
Federico MH 7737

Inelastic Light Scattering



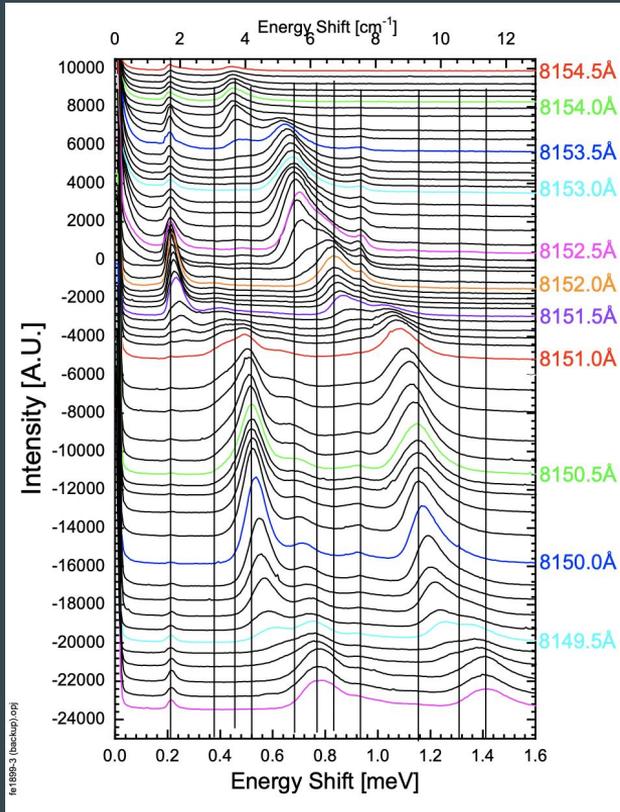
Light scattering probes the dispersive excitations of many physical systems

Aron the experimentalist: keep it simple



- “Simple” experimental setup
- Paper copies of all spectra (held up to the light to see changes)!
- Just get the data!

Aron the data analyst: never stop analyzing



- GaAs/AlGaAs 2DEG sample 1-08-97.1 grown by Loren Pfeiffer and Ken West
- Data acquired over a two-day resonance scan started on Feb. 18, 1999
- Never stop analyzing data
- Sometimes you have a question and look for the answer, and sometimes you have the answer (data) and look for the question

Optical Anomalies of the Two-Dimensional Electron Gas in the Extreme Magnetic Quantum Limit

D. Hamaoui and B. B. Goldberg

Fracini Rivier National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

A. Pinczuk, C. W. Tu, A. C. Gossard,¹ and J. H. English^{1,2}

¹AT&T Bell Laboratories, Murray Hill, New Jersey 07974

²Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Band-gap optical recombination from the two-dimensional electron gas in GaAs/AlGaAs quantum wells was measured in the regime of the fractional quantum Hall effect. New intrinsic emission lines at the Landau-level filling factor $\nu = 1$ and $\nu = 0.5$. The anomaly near $\nu = 1$ is associated with changes in population of the lowest spin-split Landau level. The optical doublet observed near $\nu = 1$ has a striking temperature dependence below $T = 2$ K similar to the magnetoresistance ρ_{xx} associated with the many-body quantum Hall.

PACS numbers: 73.20.Dg, 73.40.Gg, 73.63.Fg

Observation of the fractional quantum Hall effect (FQHE)^{1,2} are understood as evidence of condensation of the two-dimensional (2D) electron gas into an incompressible fluid with quasiparticle excitations having fractional-charged states. The FQHE is observed in magnetoresistance experiments as plateaus in the Hall resistance and minima in the diagonal resistivity at fractional values of the Landau-level filling factor having an odd denominator. Magneto-optical experiments in the FQHE regime could reveal physics of the many-body condensate that is not accessible in magnetoresistance. Results have been reported for optical indirect-semiconductor diode structures, at $\nu = 1$ and $\nu = 1.5$, and in modulation-doped GaAs-AlGaAs quantum wells at $\nu = 1$ and $\nu = 1.5$.^{3,4}

This Letter presents results of optical spectroscopy of the 2D electrons in magnetic fields of up to 30 T and temperature $T \approx 0.4$ K. In this extreme magnetic quantum limit all the electronic states in the lowest spin-split Landau level. The experiments were carried out on high-mobility GaAs quantum wells by measurements of the intrinsic optical emission due to recombination of electrons in the 2D electron gas with holes in the valence Landau level. We observe two remarkable anomalies in the optical emission. The first anomaly occurs at the new recombination line energies at a slightly higher energy than the intrinsic line and becomes dominant with increasing magnetic field. The second anomaly occurs for filling factors $\nu = 0.5$ and involves high-energy emission line appears. At $\nu = 1$ the low-temperature optical recombination doublet that first was reported dominates. The temperature dependence of these anomalies are very different. The one at $\nu = 1$ has no variation for $T < 2$ K, while the doublet at $\nu = 0.5$ changes rapidly in the measured temperature range 0.4 K < T < 2.5 K. The temperature dependence of the optical emission at $\nu = 1$ is similar to that of the diagonal magnetoresistance-

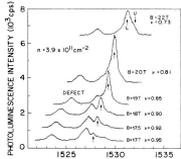


FIG. 1. Photoluminescence spectra of the 2D electron gas in GaAs/AlGaAs quantum wells. The arrows indicate the new peak appearing for $\nu = 1$. The second anomaly is identified by the new feature labeled at $\nu = 0.5$.

Observation of Flat Bands in Gate-Semiconductor Artificial Graphene

Lingjie Du,^{1,2} Ziyu Liang,¹ Shaoh J. Wang,¹ Yanqin Peng,^{1,3} Yan W. Wang,¹ Saad Fakhri,⁴ Loren N. Pfeiffer,⁵ Michael J. Manias,¹ and Aron Pinczuk^{1,11}

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²Department of Applied Physics and Applied Mathematics, CityU Hong Kong, New York, New York 10027, USA

³Department of Physics, Columbia University, New York, New York 10027, USA

⁴Italian Institute of Technology, Graphene Labs, Via Mesopic 51, I-10129 Genova, Italy

⁵Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08542, USA

⁶Department of Physics and Astronomy, and School of Materials Engineering, and

⁷School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA

(Received 17 October 2010; accepted 19 February 2011; published 12 March 2011)

The bands near M points in the Brillouin zone are the features of honeycomb symmetry in artificial graphene (AG) where electrons may condense into novel correlated phases. Here we report the observation of two low-lying doublets of AG in GaAs quantum well structures, which present the evidence of the bands in semiconductor AG. Two emerging peaks in photoluminescence spectra tuned by backgate voltage probe the singlet-doublet of AG for flat bands and demonstrate their accessibility to the Fermi level. As the Fermi level crosses the doublet, the spectra display dramatic stability against electron density, indicating interplays between electron-electron interaction and honeycomb symmetry. Our results provide a new flexible platform to explore intriguing flat-band physics.

DOI: 10.1103/PhysRevLett.106.106402

PACS numbers: 73.20.Dg, 73.40.Gg, 73.63.Fg

In two-dimensional electron systems (2DES), insulating layers. Optical emission (photoluminescence, PL) could offer direct probes of the electron DOS in GaAs AG. PL spectra are from optical recombination transitions between mobile electrons in conduction bands (CB) and weakly photoexcited holes in valence bands (VB). Holes in GaAs AG have nearly degenerate VB, so that the line shapes of PL spectra offer direct insights on the electron DOS [15–17]. The evolution of PL spectra as a function of E_F enabled by gating semiconductor AG would distinguish emerging optical characteristics.

In this Letter we report the evidence of flat bands in carrier-density-dependent PL experiments in semiconductor AG on a GaAs QW where the electron density is tuned by a voltage V_g applied to a backgate fabricated in the device. PL spectra probe a striking emission doublet that occurs when E_F crosses the flat-band doublet in AG. The energy splitting of the characteristic PL doublet is well described by the DOS singularities of flat bands near M points. The carrier-density dependence of the PL doublet further identifies it as the $\nu = 0.5$ doublet of flat bands. The recombination energies and line shapes of emission doublet remain constant over a wide range of V_g , revealing remarkable interplay between Coulomb interactions and honeycomb symmetry of electrons. The tunability of E_F in the bands would enable the construction of novel quantum phases in manufactured semiconductor devices.

Figure 1 shows the PL spectra of this graphene film that are essential to confirm the presence of flat bands that are not seen in Dirac fermions in molecular AG [14], but are difficult to apply on semiconductor AG band under

Electric Field Effect Tuning of Electron-Phonon Coupling in Graphene

Jun Yan,¹ Yuanbo Zhang,¹ Philip Kim,¹ and Aron Pinczuk^{1,2}

¹Department of Physics, Columbia University, New York, New York 10027, USA

²Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 10027, USA

(Received 22 December 2010; published 18 April 2011)

Gate-modulated low-temperature Raman spectra reveal that the electric field effect (EFE) prevails in contemporary graphene, has marked impacts on long-wavelength optical phonons of graphene. The EFE in the two-dimensional honeycomb lattice of carbon atoms creates large density modulations of carriers with linear dispersion (known as Dirac fermions). Our EFE Raman spectra display the intercrossing of lattice vibrations with these unusual carriers. The changes of phonon frequency and linewidth demonstrate optically the particle-hole symmetry about the charge-neutral Dirac point. The linear dependence of the phonon frequency on the EFE-modulated Fermi energy is explained as the electron-phonon coupling of massless Dirac fermions.

DOI: 10.1103/PhysRevLett.107.168602

PACS numbers: 73.43.-f, 62.10.+k, 73.20.Dg, 73.63.Fg

flat method to probe the EFE in a single atomic layer and the phonon dynamics that are associated with the two-dimensional (2D) Dirac fermions.

We focus on the doubly degenerate optical phonon of E_2 symmetry at ~ 1500 cm⁻¹, known as the ν band. We also report on the smaller impacts of EFE on the second-order band at ~ 2700 cm⁻¹, known as the ν' band. These two bands are prominent Raman features in graphene [17–19]. The ν band is the optical phonon at long wavelengths, and the ν' band is associated with a two-phonon state in which each phonon has a large vector q . Our experiments demonstrate that the ν band is markedly sensitive to coupling with Dirac fermions excitations at small wave vectors (long wavelengths), while the reduced impact of

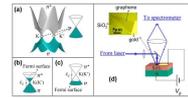


FIG. 1. (color online). (a)–(c) Electronic band structure of graphene and the experimental setup. (a) ν and ν' bands of graphene in momentum space. K and K' (Dirac points) are the corner points of the Brillouin zone. The shaded region is the ν band K recombination line, above and below shading is the dispersion of free-layer and single-layer graphene [15,16]. (b) Raman spectra of the ν band measured exhibit linear dispersion, shown as two lines of K and K' . (c) shows the region near Dirac points, the band structure exhibits linear dispersion, shown as two lines of K and K' . (d) shows the region near Dirac points of this graphene film, it is the onset region for vertical excitations by parabolic bands. (e) is the slope of the ν band. (f) Layer left is an optical image of the sample.

Remarkable!

Intriguing!

Venue!

Building a new lab at Columbia



Setting up a lab is hard work

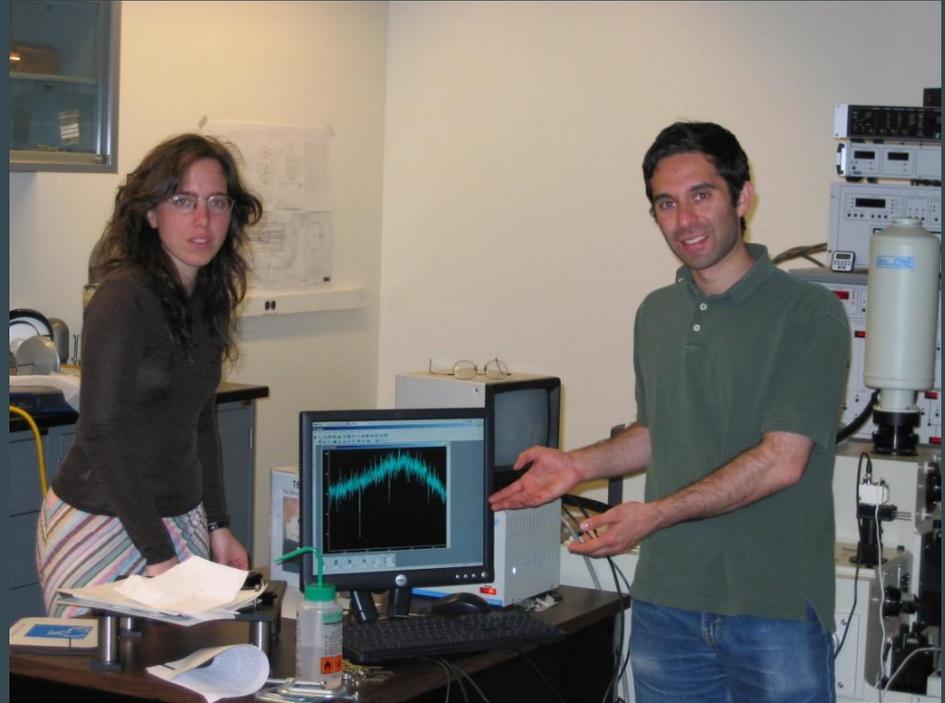


- Before you can fill a lab, you have to empty it
- Accidents happen, especially in shipping
- Be friendly with service engineers
- Testing is crucial

Hard work pays off

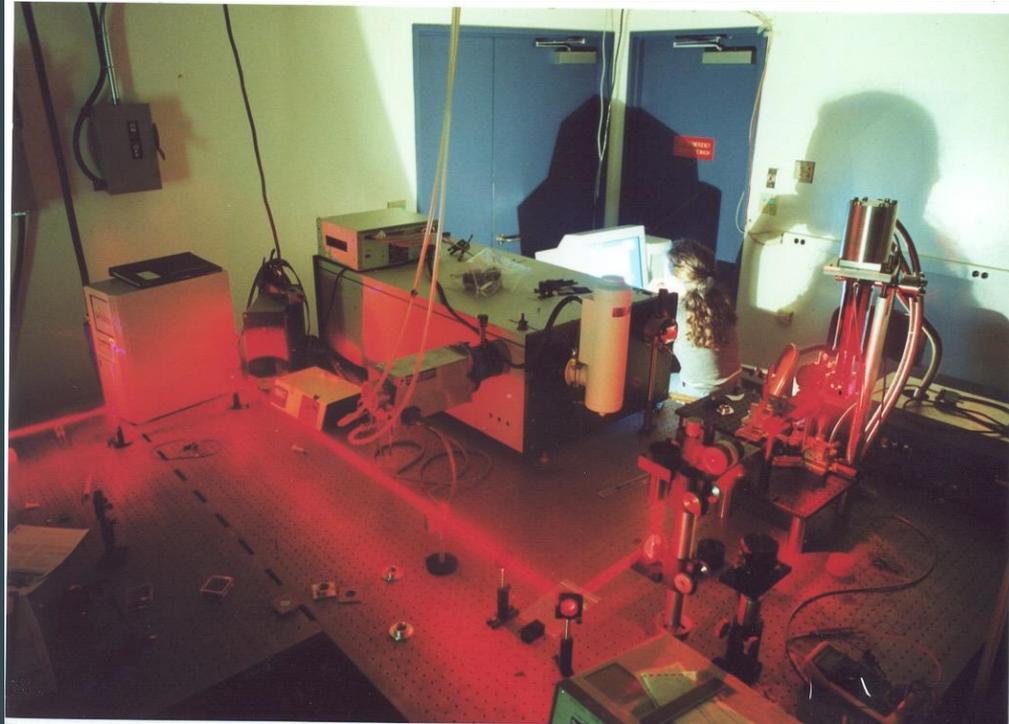


Early 2004?



Now we can graduate?!

Aron the negotiator



- Always ask suppliers for discounts ... again and again and again!
- Free is even better!

Aron the teacher: deadlines are optional

Solid State Physics
G6081, Fall 2001
Homework 4
Due October 10, 2001

Problem 1

Show that Bravais lattices that incorporate rotation axes $\phi_n = 2\pi/n$ with $n=5$ do not exist. Interpret this mathematical result.

Problem 2

Consider the conventional unit cell of an orthorhombic structure ($a \neq b \neq c$ and $\alpha = \beta = \gamma = \pi/2$) of side $a=2$, $b=3$, $c=4$. What is the distance between planes of the family $\{112\}$

Problem 3

Consider the bcc structure with every lattice point occupied by the same kind of atom. How will the allowed Bragg reflections, (h, k, l) be affected as the coordinates of the body-centered atom change from

$$\frac{1}{2}, \frac{1}{2}, \frac{1}{2} \text{ to } \frac{1}{2n}, \frac{1}{2n}, \frac{1}{2n}$$

assuming n is a positive integer? Do the calculation for $n=2$.

Problem 4

Is the honeycomb net a Bravais lattice? Why? ([see](#) fig 4.17 of Ashcroft-Mermin)

Problem 5

- Show that the reciprocal of the reciprocal lattice is a direct lattice
- Show that the reciprocal lattice of a BCC is FCC and vice-versa

Problem 6

Construct the reciprocal lattice of the square lattice and the hexagonal lattice

Aron the motivator: chocolate



Aron's network



Aron the traveler



We were lucky and were able to join several international conferences

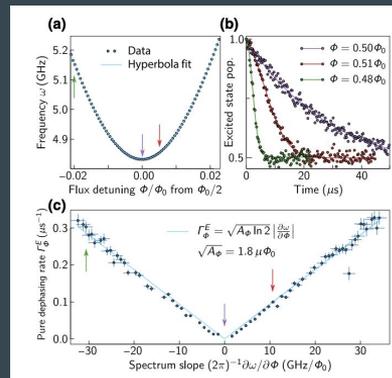
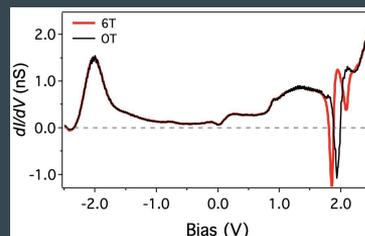
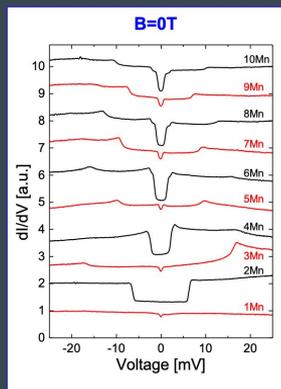
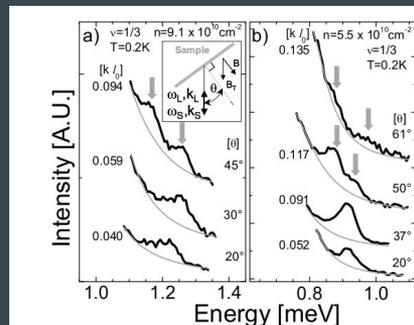
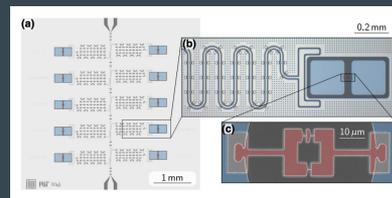
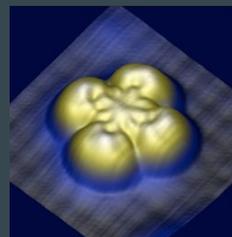
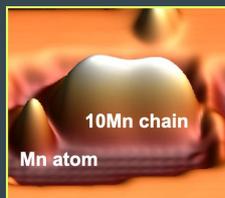
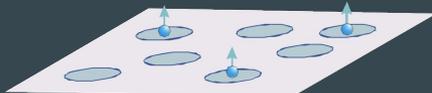
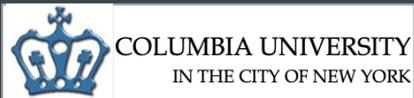
CEPSR 9th Floor Community: the Golden Age



Aron the proud advisor

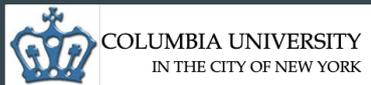
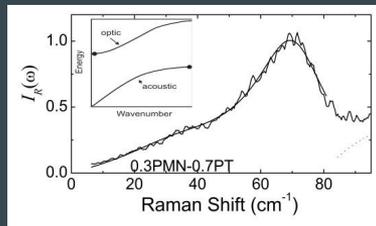
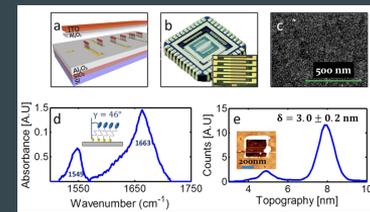
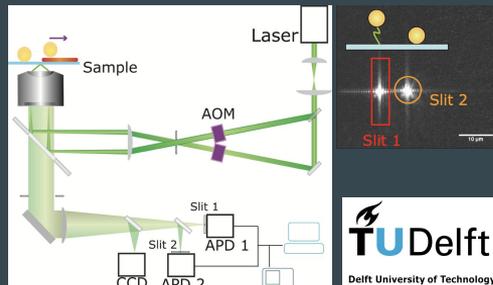
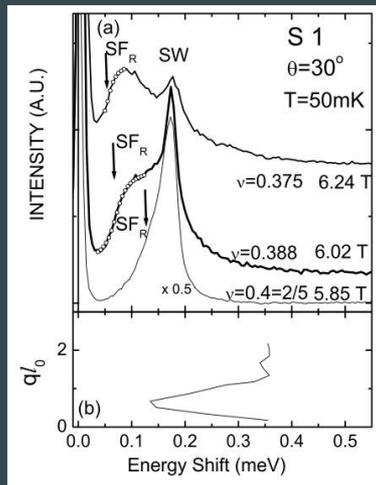


Aron's impact on our careers: Cyrus

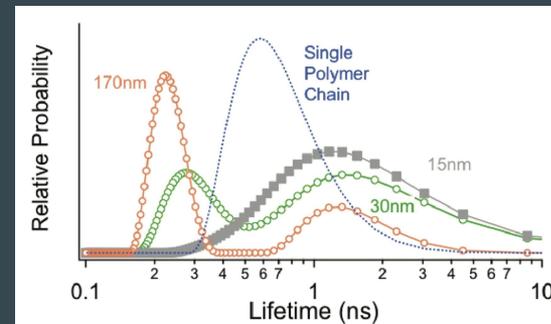


Spectroscopy has been a common thread through many different fields of study

Aron's impact on our careers: Irene



UMass Amh



Optics has been a common thread through many different fields of study

Aron's impact on our careers: Rui

Graduate student
2002-2006



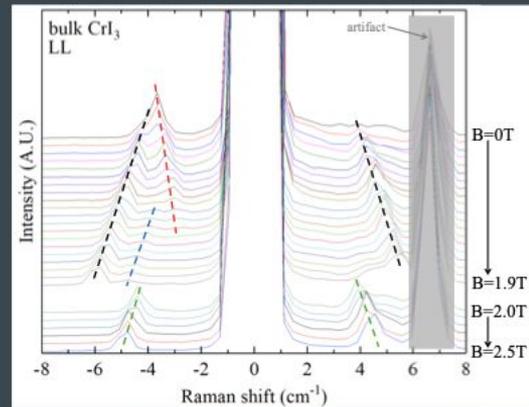
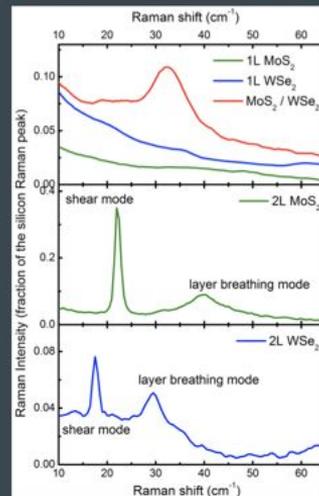
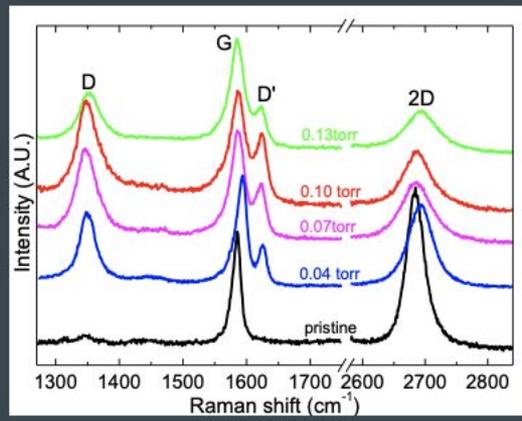
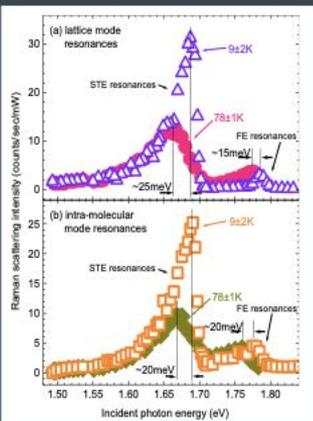
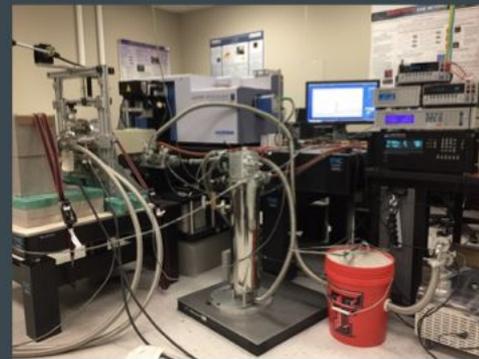
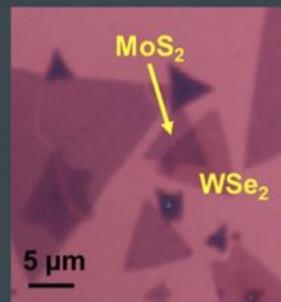
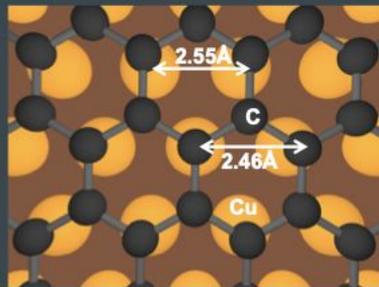
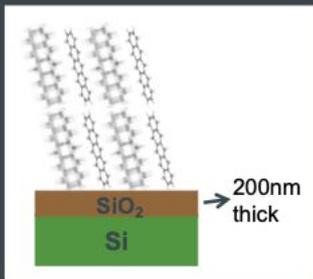
Postdoc
2009-2011



2011-2017



2017-now



Around the world

June 8, 2009 Rui met with Aron and Gladys in Beijing, China.



2006 ID met Aron and Gladys in Amsterdam



Aug. 27, 2007 Cyrus met with Aron in Los Gatos, CA



Aug. 29, 2013 Cyrus met with Aron and Gladys in London, UK

Aron the supporter



Thank you, Aron!



We will miss you!