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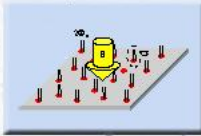


# Department of Condensed Matter Physics

## Faculty

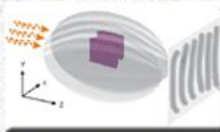
### The Theoretical Groups

Ady Stern



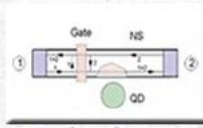
Quantum Electronic Phenomena

Ehud Altman



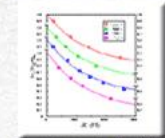
Quantum condensed Matter

Yehoshua Levinson

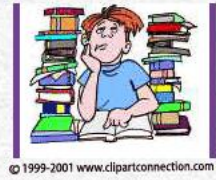


Semiconductor Physics

A. Finkel'stein

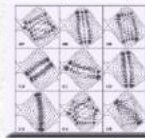


Condensed Matter Physics



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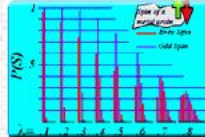
Mesoscopic Physics

Yuval Gefen



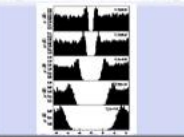
Nanophysics and Spintronics

Yuval Oreg



Confined Correlated Electrons

Shimon Levit



Condensed Matter Physics

### The Experimental Groups

Dan Shahar



Low Temperature



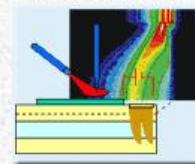
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Eli Zeldov



Superconductivity

Israel Bar-Joseph



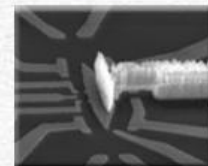
Optical Spectroscopy

Shahal Ilani



Nanoelectronics

Moty Heiblum



Transport

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# Department of Condensed Matter Physics

## Research Facilities



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**SEM**



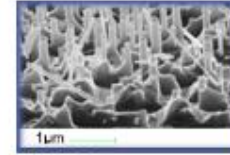
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Dr. Diana Mahalu  
Eng. Olga Raslin

With the support of:  
Eng. Yoram Rotblat

## Typical Scientific Projects

# Observation of neutral modes in the fractional quantum Hall regime

Aveek Bid, N. Ofek, H. Inoue, M. Heiblum, C. L. Kane, V. Umansky & D. Mahalu

[Affiliations](#) | [Contributions](#) | [Corresponding author](#)

*Nature* **466**, 585–590 (29 July 2010) | doi:10.1038/nature09277

Received 01 April 2010 | Accepted 17 June 2010

## Abstract

[Abstract](#) • [Introduction](#) • [Neutral edge in the  \$\nu\_b = 2/3\$  state](#) • [Sample and set-up](#) •

[Measurements of the  \$\nu\_b = 2/3\$  state](#) • [Measurements of the  \$\nu\_b = 3/5\$  state](#) • [Measurements of the  \$\nu\_b = 5/2\$  state](#) •

[Discussion](#) • [References](#) • [Acknowledgements](#) • [Author information](#) • [Supplementary information](#) •

[Comments](#)

The quantum Hall effect takes place in a two-dimensional electron gas under a strong magnetic field and involves current flow along the edges of the sample. For some particle–hole conjugate states of the fractional regime (for example, with fillings between 1/2 and 1 of the lowest Landau level), early predictions suggested the presence of counter-propagating edge currents in addition to the expected ones. When this did not agree with the measured conductance, it was suggested that disorder and interactions will lead to counter-propagating modes that carry only energy—the so called neutral modes. In addition, a neutral upstream mode (the Majorana mode) was expected for selected wavefunctions proposed for the even-denominator filling 5/2. Here we report the direct observation of counter-propagating neutral

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## Professor Mordehai(Moty) Heiblum

Graduated with a Ph.D. from U. C. Berkeley; spent 12 years with IBM Research Center in Yorktown Heights, and is currently a Professor in the Condensed Matter Physics Department (from 1991). Presently serving as the director of the Braun Center for Submicron Research and the department chair. An incumbent of the Alex and Ida Sussman Professorial Chair in Submicron Electronics.



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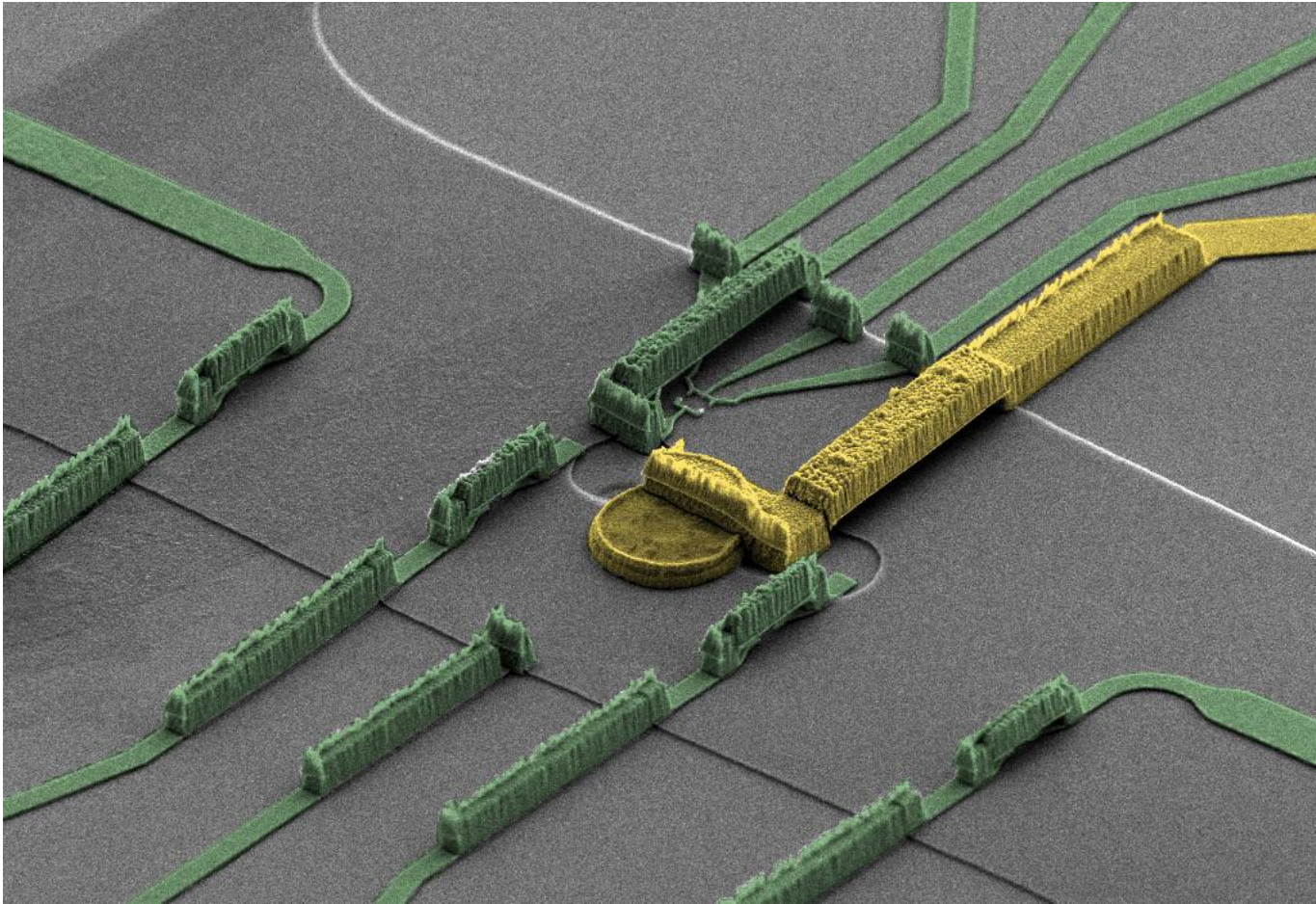


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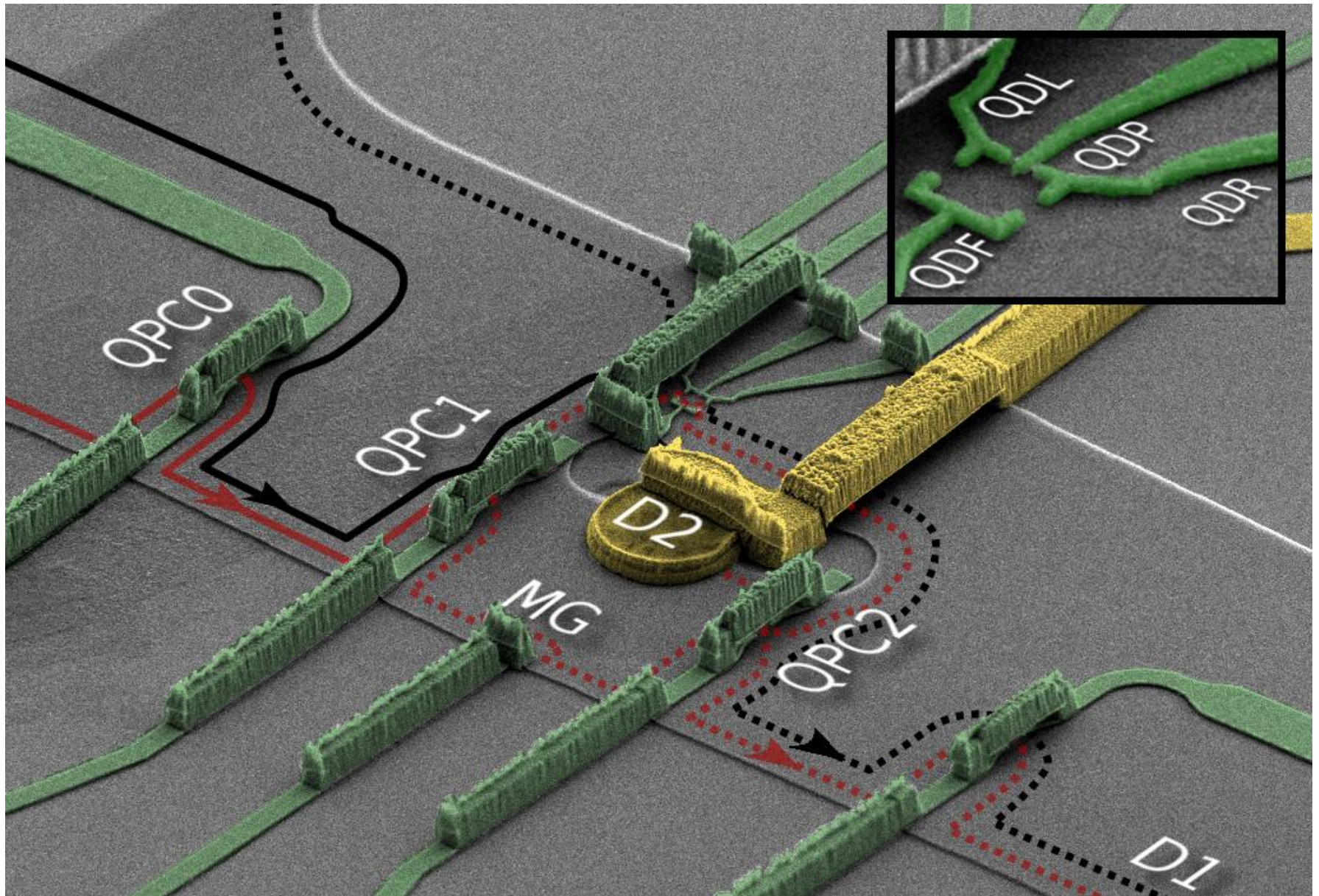
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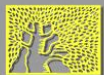
*Emil Weisz*





*Emil Weisz*

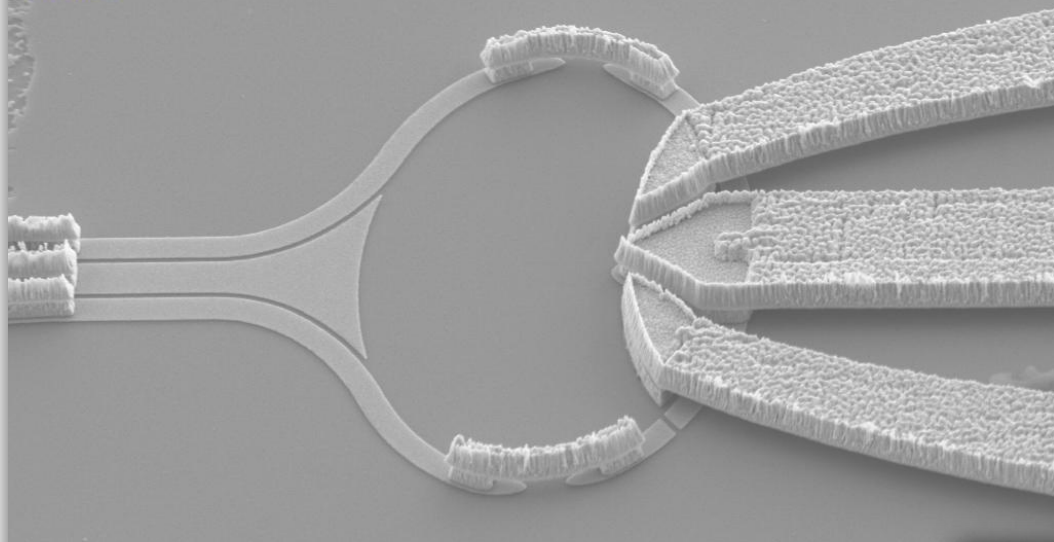




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N. Ofek

*Nissim Ofek*



2 $\mu$ m



EHT = 5.00 kV

WD = 9 mm

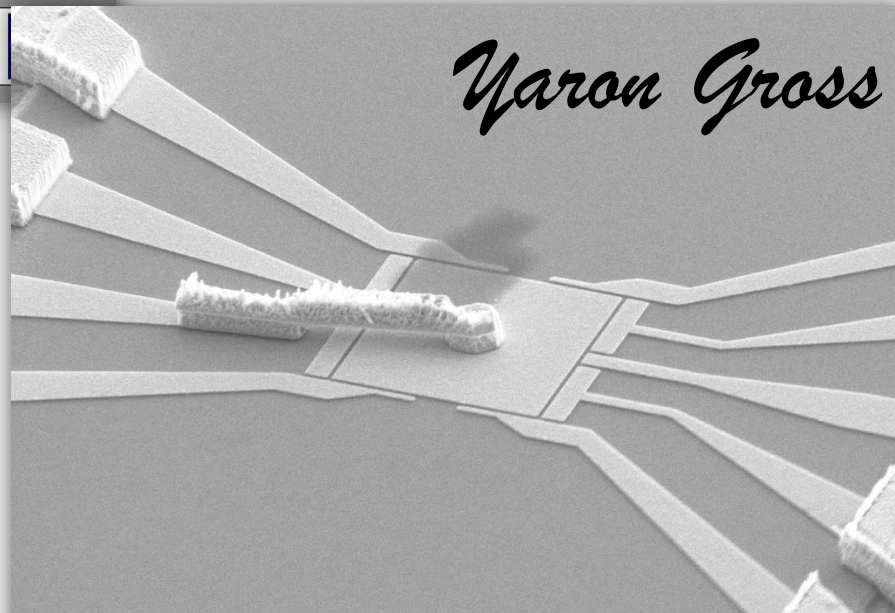
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Mag = 23.00 K X

Date :23 Nov 2010

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*Yaron Gross*



2 $\mu$ m



EHT = 5.00 kV

WD = 11 mm

Mag = 23.97 K X

Image Pixel Size = 14.7 nm

File Name = 4by4c-01.tif

Signal A = SE2

Date :15 Feb 2010

Time :13:40:16

## Self-assembly of metallic double-dot single-electron device

A. Guttman, D. Mahalu, J. Sperling, E. Cohen-Hoshen, and I. Bar-Joseph

Citation: *Appl. Phys. Lett.* **99**, 063113 (2011); doi: 10.1063/1.3624899

View online: <http://dx.doi.org/10.1063/1.3624899>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v99/i6>

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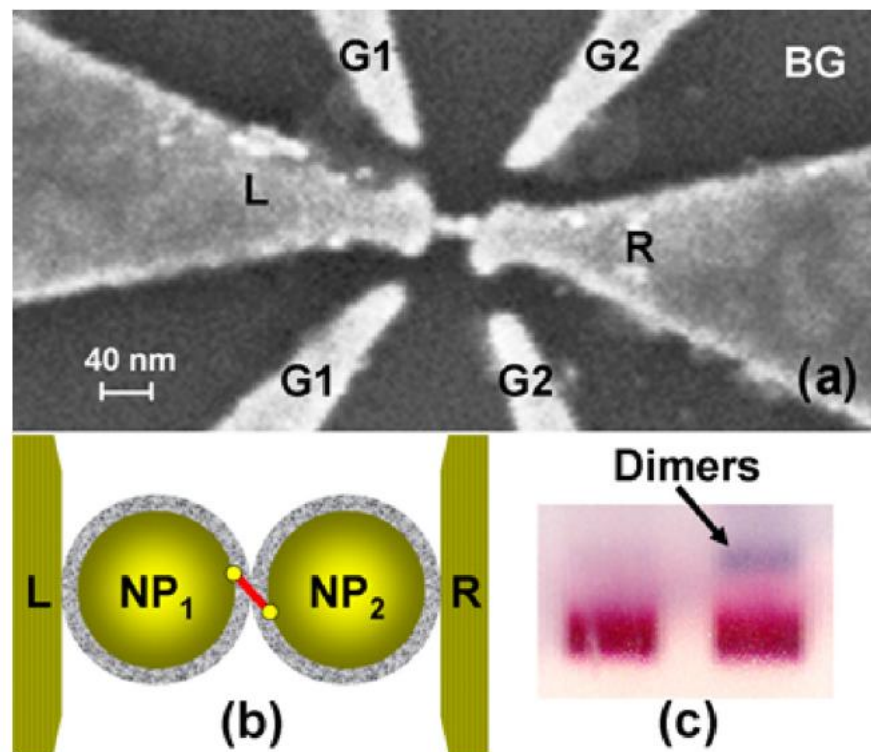
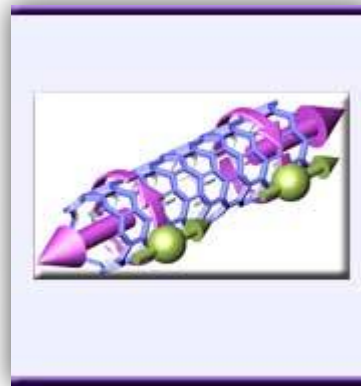
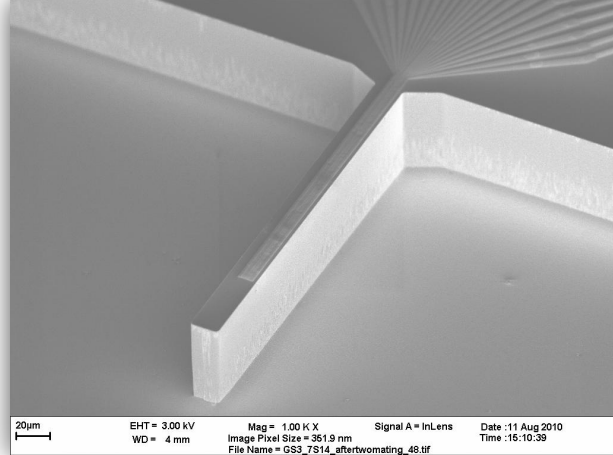


FIG. 1. (Color online) (a) Scanning electron microscope image of the double-dot device. The dimer, which is composed of 17 nm NPs, is aligned in series with the lead electrodes (L and R). (b) A sketch of the dimer and leads region, showing the capping layers and the linker molecule. (c) Gel matrix loaded with 34 nm NPs' solution that includes the linker molecule (right) and a corresponding control (left).

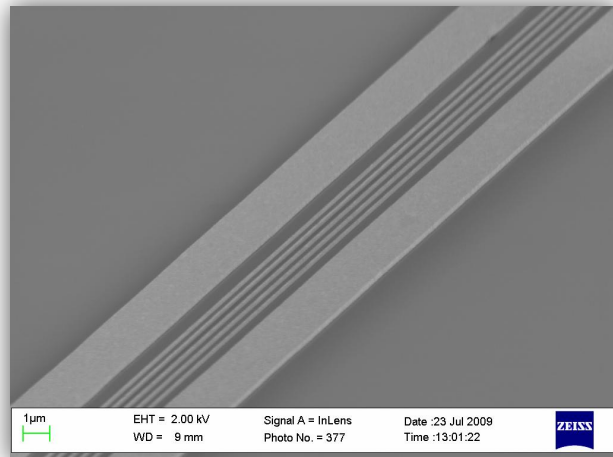




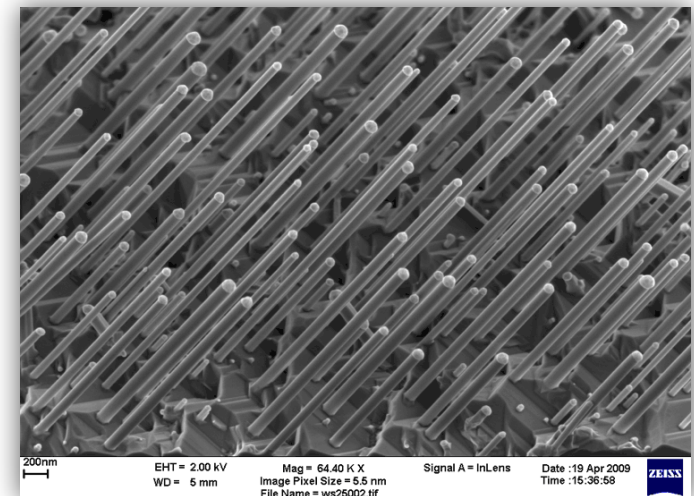
Dr Shahal Ilani

Quantum phenomena in small systems,  
such as carbon *nanotubes and graphene*  
Study of quantum behavior in highly-controlled  
settings, including:

- Physics of electrons in one and two dimensions
- Imaging of quantum phenomena on atomic scales
- Single-spin quantum manipulation



Dr Hadas Strikman •GaAs and InAs nano wires



# **Collaborations with other Centers/Universities**

## **International Programs**



# Center for Probing the Nanoscale - NSF NSEC Grant 0830228

PI: Kathryn Moler, Co-PI: David Goldhaber-Gordon

Stanford University, Stanford, CA 94305



Stanford University and IBM Corporation, with funding from National Science Foundation, founded the Center for Probing the Nanoscale to achieve five principal goals, to:

## About the Center for Probing the Nanoscale

- develop novel probes that dramatically improve our capability to observe, manipulate, and control nanoscale objects and phenomena
- educate the next generation of scientists and engineers regarding the theory and practice of these probes
- apply these novel probes to answer fundamental questions in science and technology
- transfer our technology to industry in order to make these novel probes widely available
- inspire students, teachers and the public about nanotechnology



Stanford University

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## Department of Physics

### People

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## Research Interests

### Experimental Condensed Matter

Research focuses on electrons in reduced dimensions: 2-dimensional electron gases, quantum wires and point contacts, and quantum dots, especially the role of interactions, quantum coherence, many-body states, and spin in these systems. Many materials are used, including conventional semiconductor heterostructures, nanowires, carbon (nanotubes and graphene sheets), and organic molecules. Major tools include nanolithography, precision low-temperature electrical transport, and several novel scanning probe techniques.

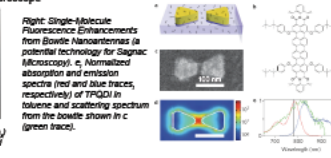
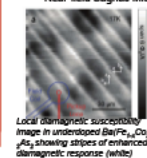
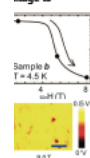
### Related research groups:

- [Experimental Condensed Matter](#)
- [Mesoscopic Physics](#)
- [Microscopy and Imaging](#)

## Individual Nanomagnet Characterization

Moler, Kirtley, Kapitulnik, Moerner

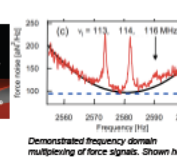
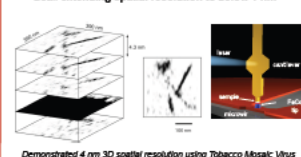
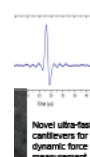
- develop and demonstrate techniques with the magnetic sensitivity and spatial resolution to characterize individual nanomagnets
- Tools under development:
  - Scanning SQUID Microscope, Scanning Hall Bar Microscope, Magnetic Force Microscope, Near-field Sagnac Microscope



## Nanoscale Magnetic Resonance Imaging

Rugar, Fruit

- Advancing development of Magnetic Force Resonance Microscopy (MFRM) toward a nanoscale structure microscope
- Non-destructive and elementally selective 3D imaging technique
- Goal: extending spatial resolution to below 1 nm



## Education and Industrial Outreach

### Resources

<http://nanoteachers.stanford.edu>

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Welcome to NanoTeachers!

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Resources for students

Workshops and Seminars

### Industrial Outreach

- Annual Nanoprobes Workshop
- Bring together academic and industrial scientists to exchange knowledge and ideas
- Broaden the horizons of participants
- Initiate research projects with industry
- Provide venue for interaction between industry and graduating students
- ~200 participants
- 13 companies
- Industry Field Trips
- Industrial Affiliates Program
- Sponsored research programs
- Participation in Center activities

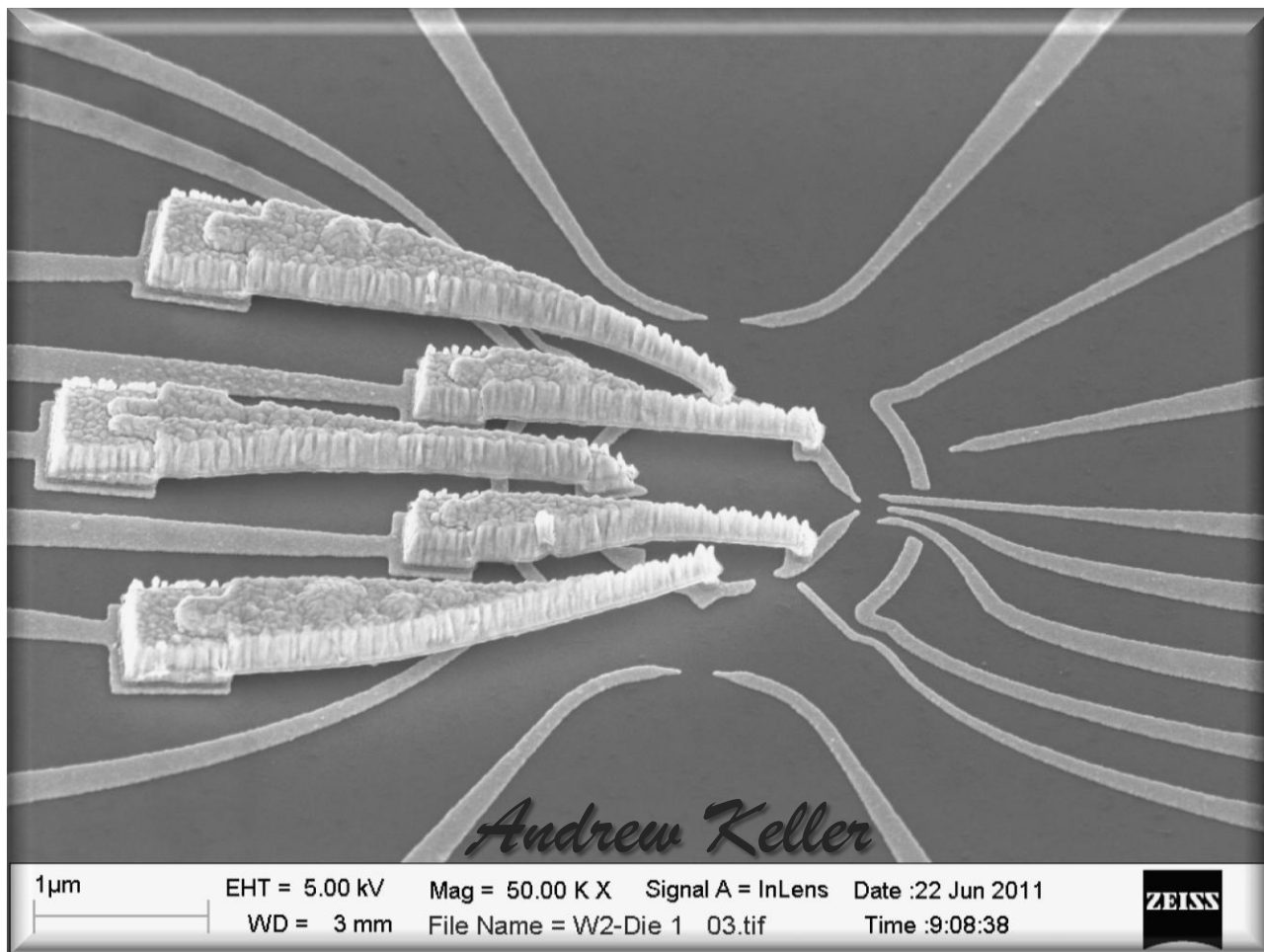
## Selected 2010 Publications

- [1] J. Kirtley, "Fundamental studies of superconductors using scanning magnetic imaging," *Rep. Prog. Phys.* **73**, 125501 (2010) [doi:10.1088/0034-4885/73/12/125501].
- [2] M. P. Jura, M. Gobbi, M. A. Topinka, L. N. Pfeiffer, K. W. West, and D. Goldhaber-Gordon, "Spatially resolved electron-electron scattering in a two-dimensional electron gas," *Phys. Rev. B* **82**, 155328 (2010) [doi:10.1103/PhysRevB.82.155328].
- [3] B. D. Almqvist, P. Verma, W. Cui, and N. A. Melosh, "Nanoscale patterning controls inorganic-membrane interface structure," *Nanoscale* (2010) [doi:10.1039/c9nr00486c].
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- [9] C. Hicks, J. Kirtley, T. Lippman, N. Koshnick, M. Huber, Y. Maeno, W. Yuhua, M. Maple, and K. Moler, "Limits on superconductivity-related magnetization in  $\text{Sb}_2\text{Te}_3$  and  $\text{PbSbTe}$  from scanning SQUID microscopy," *Physical Review B* **81** (2010) [doi:10.1103/PhysRevB.81.234501].
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NATURE PHYSICS | LETTER

## Dephasing time of GaAs electron-spin qubits coupled to a nuclear bath exceeding 200 $\mu$ s






Hendrik Bluhm, Sandra Foletti, Izhar Neder, Mark Rudner, Diana Mahalu, Vladimir Umansky & Amir Yacoby

[Affiliations](#) | [Contributions](#) | [Corresponding author](#)

*Nature Physics* 7, 109–113 (2011) | doi:10.1038/nphys1856

Received 10 June 2010 | Accepted 20 October 2010 | Published online 12 December 2010

Qubits, the quantum mechanical bits required for quantum computing, must retain their quantum states for times long enough to allow the information contained in them to be processed. In many types of electron-spin qubits, the primary source of information loss is decoherence due to the interaction with nuclear spins of the host lattice. For electrons in gate-defined GaAs quantum dots, spin-echo measurements have revealed coherence times of about 1  $\mu$ s at

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Hendrik Bluhm, Sandra Foletti, Izhar Neder, Mark Rudner & Amir Yacoby

Braun Center for Submicron Research, Department of Condensed Matter Physics, Weizmann

Institute of Science, Rehovot 76100, Israel


Diana Mahalu & Vladimir Umansky

### Contributions

Electron-beam lithography and molecular-beam-epitaxy growth were carried out by D.M. and V.U., respectively. H.B., S.F. and A.Y. fabricated the sample, planned and executed the experiment and analysed the data. I.N., M.R., H.B. and A.Y. developed the theoretical model. H.B., S.F., I.N., M.R. and A.Y. wrote the paper.

Harvard University

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## FACULTY

### Amir Yacoby


**Professor of Physics**  
**PhD 1994, Weizmann Institute of Science**

---

Professor Yacoby is an experimental condensed matter physicist. His current research interests are focused at unraveling the underlying phenomena governing low dimensional systems. Starting with two dimensional electron systems, the group uses novel scan probe techniques that are capable of detecting electric charge with a resolution of  $10^{-4}$  of one electron and spatial resolution of 100nm. This technique enables them to image the distribution of electrons and the way they localize in space in various material systems such as GaAs or single monolayers of graphite as well as under various ground state conditions such as the integer and fractional quantum Hall effect. Of particular interest is the 5/2 fractional quantum Hall ground state where the elementary excitations carry a fractional charge of  $e/4$  and obey non-Abelian statistics. Such a system is a model system for topological quantum computation.

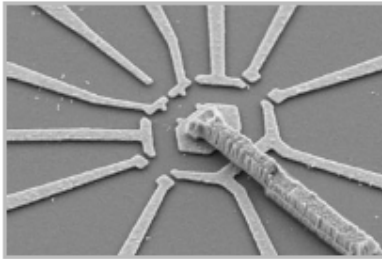
Reducing dimensionality further to one dimension opens up a fascinating world where electrical conduction is strongly governed by the interaction between electrons. Here the group explores experimentally Luttinger liquid behavior whose strongest manifestation is the separation of spin and charge of the elementary excitations.

Finally going down to zero dimensional systems, know as quantum dots, the group studies various approaches to storing and manipulating quantum information using the spin of individual electrons.



## Mesoscopic and Quantum Device Laboratory

In Mesoscopic and Quantum Device Laboratory, we study quantum-mechanical properties of electrons in quantum devices such as electron interferometer, quantum dots and etc. To achieve this goal, we study electron transport through our quantum devices at an extremely low temperature (~around 10mK) in a dilution fridge. To fabricate such quantum device, electron-beam lithography technique is used. The SEM picture shown below is one example picture of our devices.



An electron interferometer fabricated on top of ultra-high mobility 2DEG wafer with a quantum dot embedded inside the interferometer and a nearby electron detector to collect path information of the electrons inside the interferometer. The overall size of the device (honey-comb-shaped structure) is around 1  $\mu\text{m}$  in diameter.

Currently, we are interested in observing single electron interference and realizing spin entangled quantum states of electrons by using two-path electron interferometer, which is quite similar to the one described above. We are also interested in observing orbital Kondo effect by using parallel double quantum dots.

## Collaborators

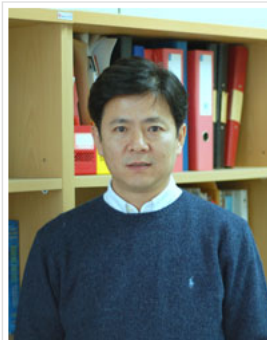
We really thank to our collaborators who have been helping us in many ways and supportive for years. The links shown below are our collaborators' websites.

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KRISs

## Professor



Name : Yunchul Chung

Homepage : <http://meso.phys.pusan.ac.kr/person/ycchung.html>

e-mail : [ycchung@pusan.ac.kr](mailto:ycchung@pusan.ac.kr)

Telephone : 051-510-2729

Education

Ph.D : 1990-1995, Physics, Korea University

M.S. : 1988-1990, Physics, Korea University

B.S. : 1984-1988, Physics, Korea University

Career

Research Associate at Oxford University, 1996 ~ 2000

Visiting Scientist at Weizmann Institute of Science, 2000 ~ 2003

Assistant Professor at Pusan National University, 2003. 11. ~ 2008. 2

Associate Professor at Pusan National University, 2008. 3. ~ present

## Fabrication and testing of highly efficient resonance domain diffractive optical elements

Proc. SPIE 8169, 81690D (2011); doi:10.1117/12.898991

Wednesday 7 September 2011

Marseille, France

Optical Fabrication, Testing, and Metrology IV

Angela Duparré, Roland Geyl

### Abstract

### References (12)

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Omri Barlev, Michael A. Golub, and Menachem Nathan  
Tel Aviv Univ. (Israel)

Asher A. Friesem and Diana Mahalu  
Weizmann Institute of Science (Israel)

Structuring of optical surfaces with surface-relief diffractive optical elements is an enabling technology for achieving considerable spatially varying changes in light propagation direction and wavefront curvature. This way, Bragg effects, angular and spectral selectivity and nearly 100% diffraction efficiency usually attributed to volume optical holograms can be achieved by surface relief computer generated holograms and diffractive optical elements. Several methods for fabricating deep "resonance domain" diffraction structures with periods, exceeding the subwavelength limit but near to the wavelength, were compared and optimized. Results of

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Proceedings of SPIE 1739, 622 (1993)

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Proceedings of SPIE 7516, 75160A (2009)

Highly efficient second-harmonic generation in mixture films of p-nitroaniline and methacrylate polymers  
Proceedings of SPIE 2025, 436 (1993)

Novel method for patterned fabric

HV	WD	VacMode	Det	Mag	
20.0 kV	8.8 mm	Low vacuum	LFD	5383x	

20.0µm  
WAMRC-TAU

Grating size: 2 mm X 2 mm (4[mm<sup>2</sup>])  
Period of 520nm and stripe width of 150nm (~ 1% error measured)  
Lift –off of Cr followed by Etching on fused silica.

Period of 520nm and stripe width of 25nm  
Lift –off of Cr followed by Etching on fused silica.

Magnification Detector Accelerating Voltage  
- ETD 20 kV

500 nm

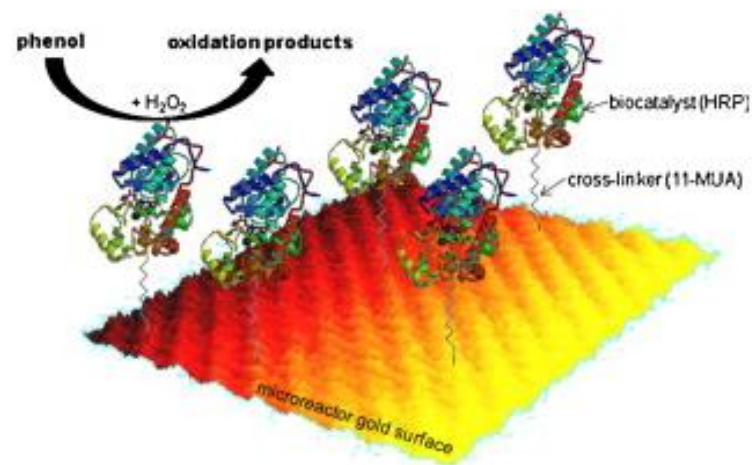


# Biocatalytic microreactor incorporating HRP anchored on micro-/nano-lithographic patterns

Madalina Tudorache<sup>a</sup>, Diana Mahalu<sup>b</sup>, Cristian Teodorescu<sup>c</sup>, Razvan Stan<sup>d</sup>, Camelia Bala<sup>e</sup>,  , Vasile I. Parvulescu<sup>a</sup>,  

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- <sup>e</sup> University of Bucharest, Department of Analytical Chemistry, Bd. Regina Elisabeta 4-12, Bucharest 030016, Romania

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WEIZMANN  
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WISSMC

The Sub-Micron Center  
A Large Scale Facility of The European Commission



PdAu honeycomb-gate on GaAs substrate  
By Dr. Diana Mahalu

General Information

Information about  
The Braun Center

The Weizmann  
Institute of Science

Application Form

The European  
Commission

LSF Program



## Special Electron Beam Lithography WorkShop

organized by

Nezih Unal (GenISys GmbH.) and

Diana Mahalu (Weizmann)

<http://www.genisys-gmbh.de/>

<http://www.weizmann.ac.il/condmat/mahalu.html>

July 14<sup>th</sup>

*Weizmann Inst. of Science – SubMicron Center*

**Session 1:** 10.00h – 13.00h

*Lunch:* 13.00h – 14.00h

**Session 2:** 14.00h -16.00h

### Session 1:

- Layout preparation strategies for e-beam writing ~45 min
  - “Cleaning” overlaps gaps
  - Design grid vs fracture grid vs shot pitch
  - Field positioning strategies
  - Writing time optimization (bordering, coarse-fine split,
- Proximity Effect and Correction strategies ~45 min



# Third dimension of proximity effect correction (PEC)

**Author(s):** Unal, N.; Mahalu, D.; Raslin, O.; Ritter, D.; Sambale, C.; Hofmann, U.

**Source:** Microelectronic Engineering **Volume:** 87 **Issue:** 5-8 **Pages:** 940-2 **Published:** May-Aug. 2010 **DOI:** 10.1016/j.mee.2009.12.002

**Abstract:** New nano applications, like T-gates, bridges, mirror arrays, blazed gratings, 3D zone plates, 3D holograms and MEMS devices require highly accurate process for high resolution patterning in lateral dimensions. The aforementioned 3D applications, imply accurate control of resist thickness, after development dimension. We show a feasibility test for a new 3D PEC approach, using Layout BEAMER e-beam lithography software. [All rights reserved Elsevier].

**Accession Number:** 11586021

**Document Type:** Journal Paper

**Language:** English

**Treatment:** Practical, Experimental

**Controlled Indexing:** electron beam lithography; nanotechnology; photoresists; proximity effect (lithography)

**Uncontrolled Indexing:** proximity effect correction; T-gates; mirror arrays; bridges; blazed gratings; 3D zone plates; 3D holograms; MEMS devices; 3D patterning process; 3D PEC approach; layout BEAMER e-beam lithography software

**Classification Codes:** B2550G Lithography (semiconductor technology)

**International Patent Classification:** B82; G03F7/00; H01L21/02

**Author Address:** Unal, N.; Ritter, D.; Sambale, C.; Hofmann, U.; GenlSys GmbH, Taufkirchen, Germany.; Mahalu, D.; Raslin, O.; Weizmann Inst. of Sci., Rehovot, Israel

**Publisher:** Elsevier Science B.V., Netherlands

**Number of References:** 3

**CODEN:** MIENEF

**ISSN:** 0167-9317

**Document Number:** S0167-9317(09)00836-3



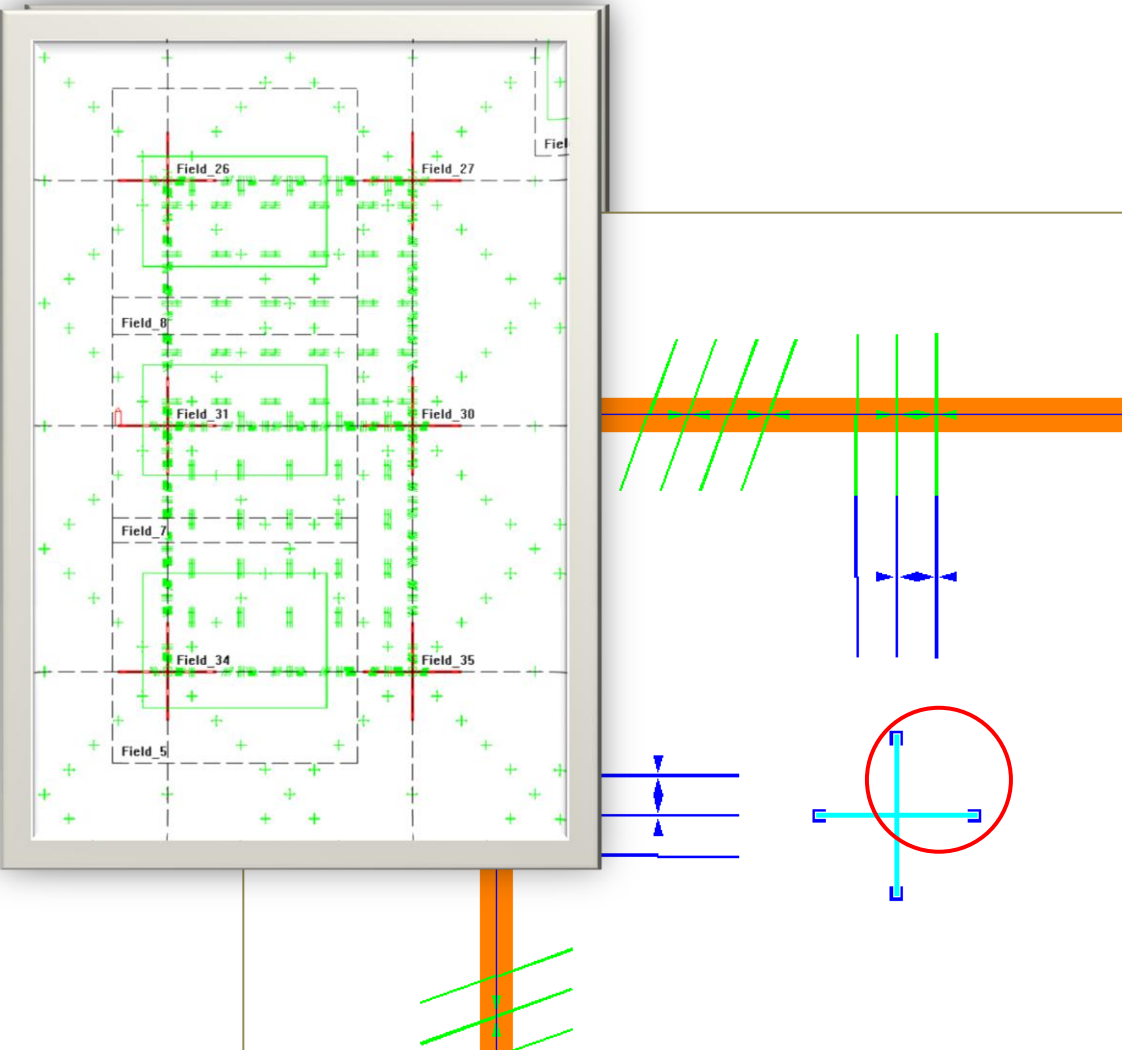
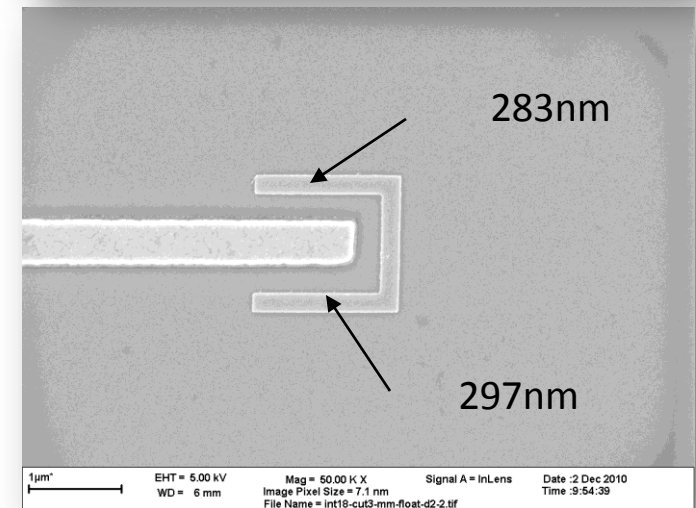
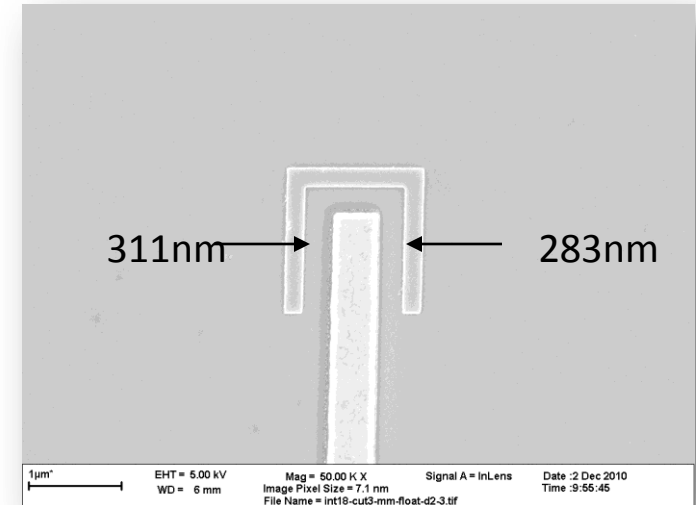


Floating Fields

こんにちは！  
**JEOL!**

## Alignment (mix and match MM - Floated)

Floated < 15nm MM alignment



# LB extract layers 34,100,110 with extraction region 101 (block size)

