Technion Technology Transfer

Technion Israel Institute of Technology

Technion Potential Contribution to the MAGNET Consortium on Development of Technologies in the Field of Quantum Sensing

23 April 2018

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Researcher	Affiliation
Prof. Gadi Eisenstein	Electrical Engineering
Prof. Meir Orenstein	Electrical Engineering
Prof. Eyal Buks	Electrical Engineering
Prof. Alex Hayat	Electrical Engineering
Prof. Moti Segev Prof. Erez Hasman	Physics and Solid State Institute Mechanical Engineering and RBNI
Prof. Yachin Ivry	Material Science and Engineering and Solid State Institute
Prof. Alon Hoffman	Chemistry
Prof. Aharon Blank	Chemistry

Prof. Gadi Eisenstein, Electrical Engineering Dept. and the Russell Berrie Nanotechnology Institute

E-mail: gad@ee.techniopn.ac.il Phone: 048294694, 0523220176

❖ Background of principal investigator:

- World leader in semiconductor laser physics and applications
- Expert in clock technology – participated in the development of NAC technology, now produced by AccuBeat

❖ Relevant activity:

- Development of unique opto-atomic clock

❖ Potential collaborators:

- AccuBeat, Rafael, Technion researchers, Weizmann Instituter researchers

OPTO-ATOMIC CLOCK

❖ A unique clock comprising

- An ultra narrow linewidth, 1-10 Hz Semiconductor lasers locked on a high Q cavity.
- A frequency comb which is disciplined by one of the narrow linewidth lasers.
- An external cavity semiconductor laser locked on a Rb transition used to compensate for drift in the high Q cavity

❖ The clock system provides:

- An ultra narrow linewidth laser, 1-10 Hz at an absolute frequency
- A comb where each comb line has a linewidth of 1-10 Hz and each line has a known absolute frequency

❖ Applications:

- High resolution Lidar systems
- Chemical sensing with high accuracy and sensitivity
- Timing and synchronization signal distribution to remote locations
- Highly accurate optical gyroscope systems

OPTO-ATOMIC CLOCK

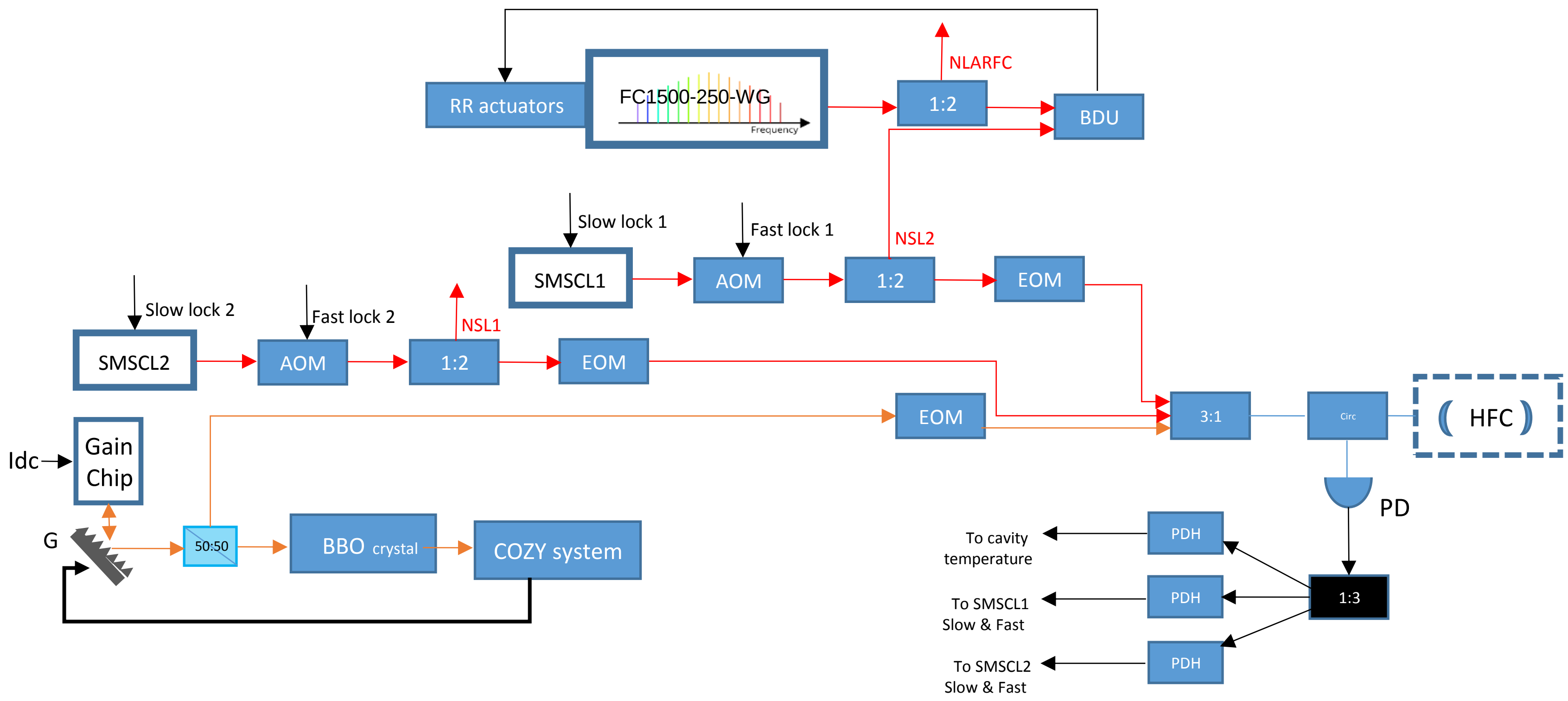

Figure: Locking Schematics for the narrow linewidth frequency comb (FC1500-250-WG). SMSCL: single mode semi-conductor laser, AOM- Acousto-optic modulator, EOM: Electro-optic modulator, PDH: pound drever Hall locking system, HFC: High finesse cavity with finesse 350000, FBS: Fiber beam splitter, FC-Lock: Frequency comb locked on SMSCL1, M: Mirror, BS: Beam splitter, GC: Gain chip, G: Grating, PD: photo-Detector, BDU: Beat Detection Unit, RR: Repetition Rate, NLARFC: Narrow linewidth atomic referenced frequency comb, NSL: narrow linewidth semiconductor laser.

Technion Technology Transfer

Quantum Sensing

in the *NanoMicroPhotonics Lab* –EE. Dept. Technion

PI: *Meir Orenstein* *meiro@ee.technion.ac.il*

Long record in quantum technologies

- Invention and development of the 2-photon light source
- Invention and development of novel quantum key distribution systems (classical Alice)
- Variety of light matter interactions in the nanoscale

Our Sensing Projects:

- Sensing magnetic, electric, temp. fields in the nano-scale using diamond color centers
- Miniature quantum Gyros using quantum silicon photonics circuitry with atoms
- Ultralow light sensing (single photons) using plasmon enhanced super conductor wires

Industrial Collaborations

- Rafael
- MAFAT

Potential Collaborators

- Israeli companies for diamond processing
- Elbit Systems
- Medical companies (magnetic and nuclear imaging)
- SCD
- Accubeat

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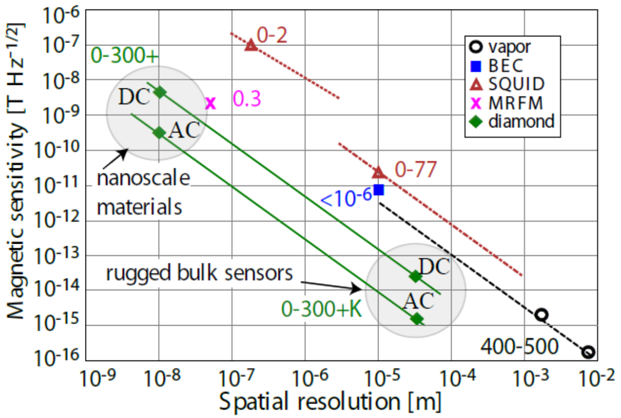
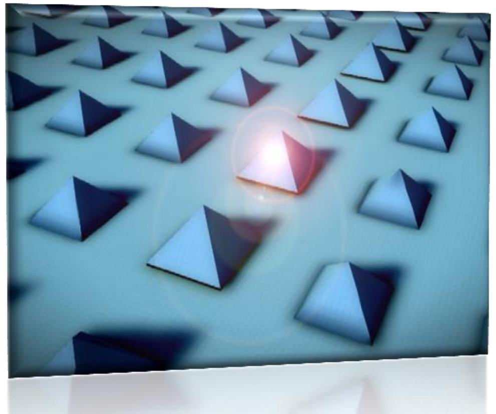
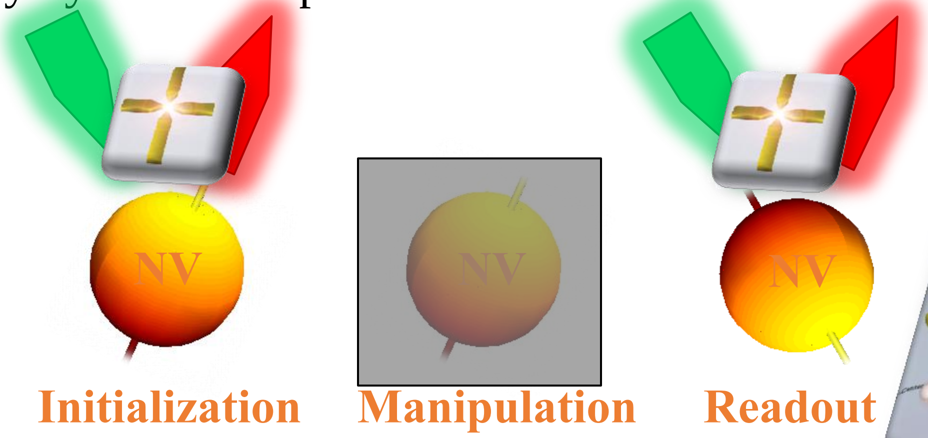
Metrology by Metal-Diamond Nanostructures

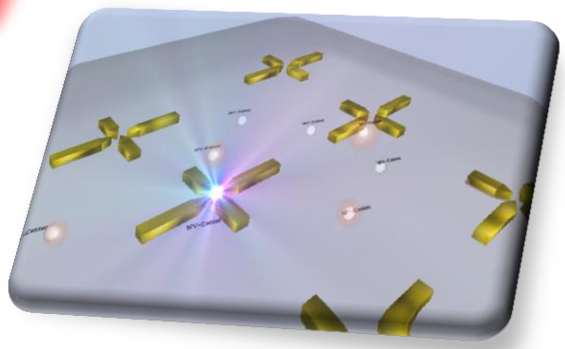
- **Quantum metrology based on Nitrogen-Vacancy centers in diamond**
  - Room-temperature nanoscale magnetometry
  - Bio-magnetometry
  - Electrometry
  - Sensitive nanoscale thermometer



- **Sensitive ODMR for nanoscale and microscale detection, based on plasmonic metal-diamond nanostructures Incorporating Nitrogen-Vacancy centers**
  - Plasmonic-Enhanced Visible fluorescence ODMR (high sensitivity at the nanoscale)
  - Broadband magnetometry by NIR absorption-detection of NV centers







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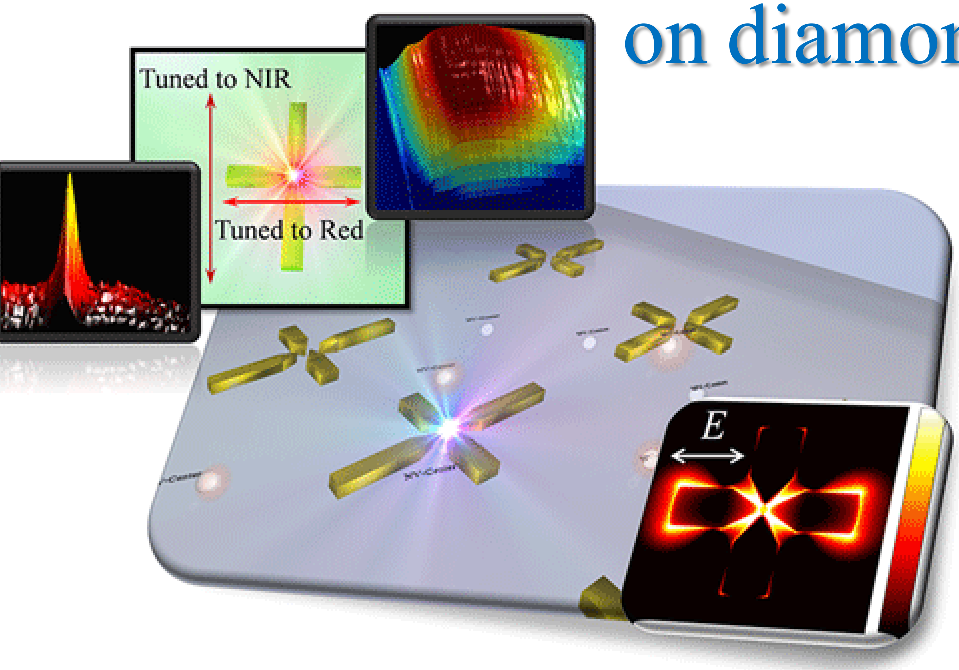
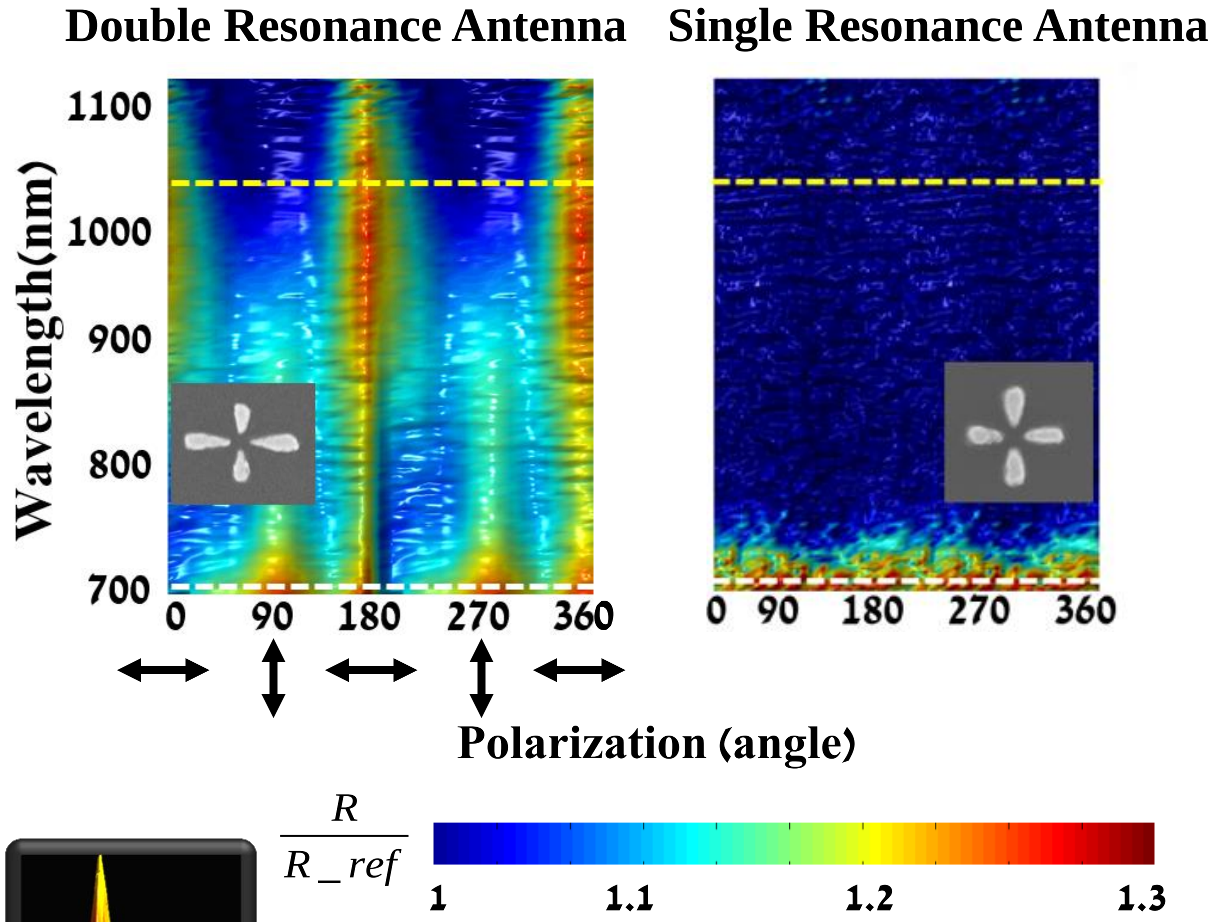
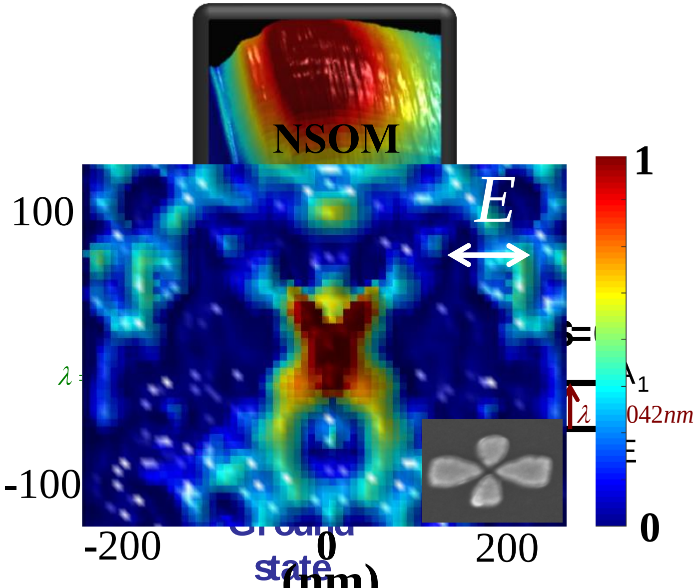
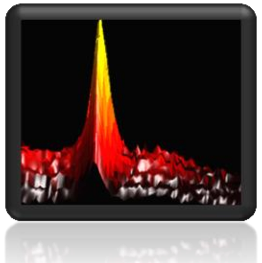
Polarized Doubly Resonant Nano-antennas for on diamond Spin States Spatial Addressing



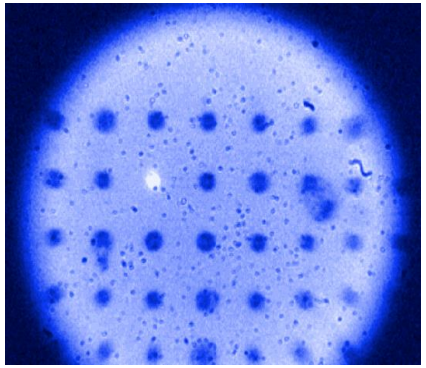


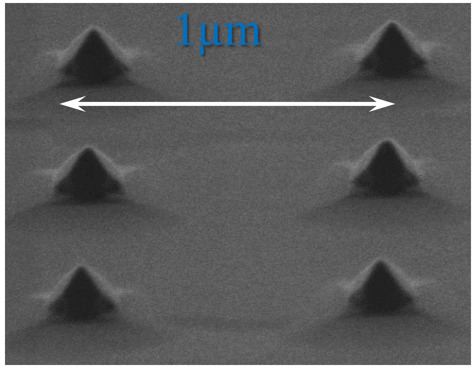


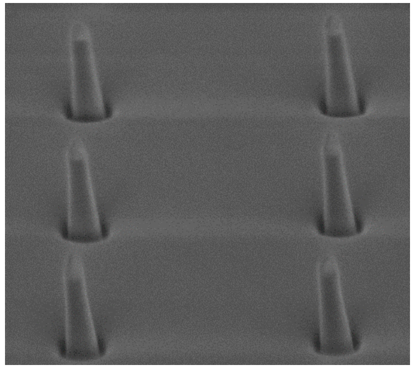


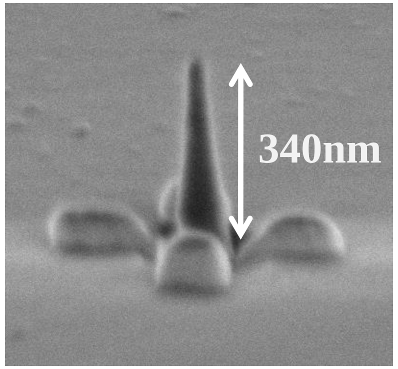
J. Tzach, et al. Nano Letters (2017).
DOI: 10.1021/acs.nanolett.7b01088

Highly Confined *Diamond-metal Nanostructures* for Magnetic Detection and Nanoscale MRI









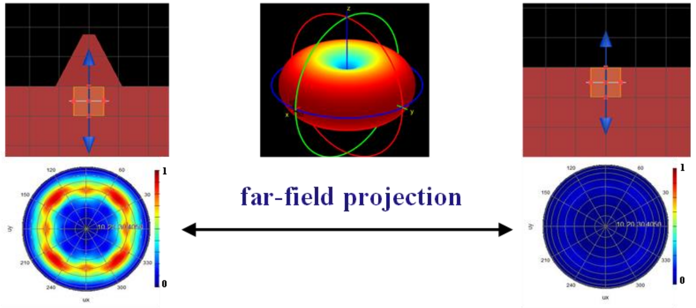
- Robust and deterministic diamond nanostructures

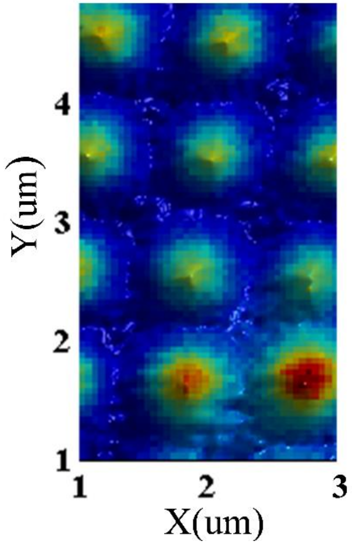
Photonic density o

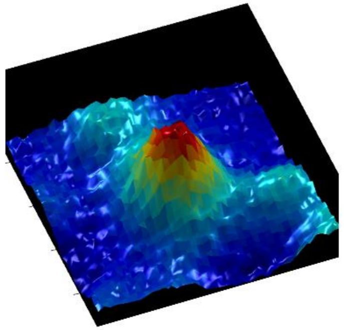
low quality factor ; highly localized mode volume.

High extraction effic

Extraction efficiency enhancement (for Z-polarized dipole):

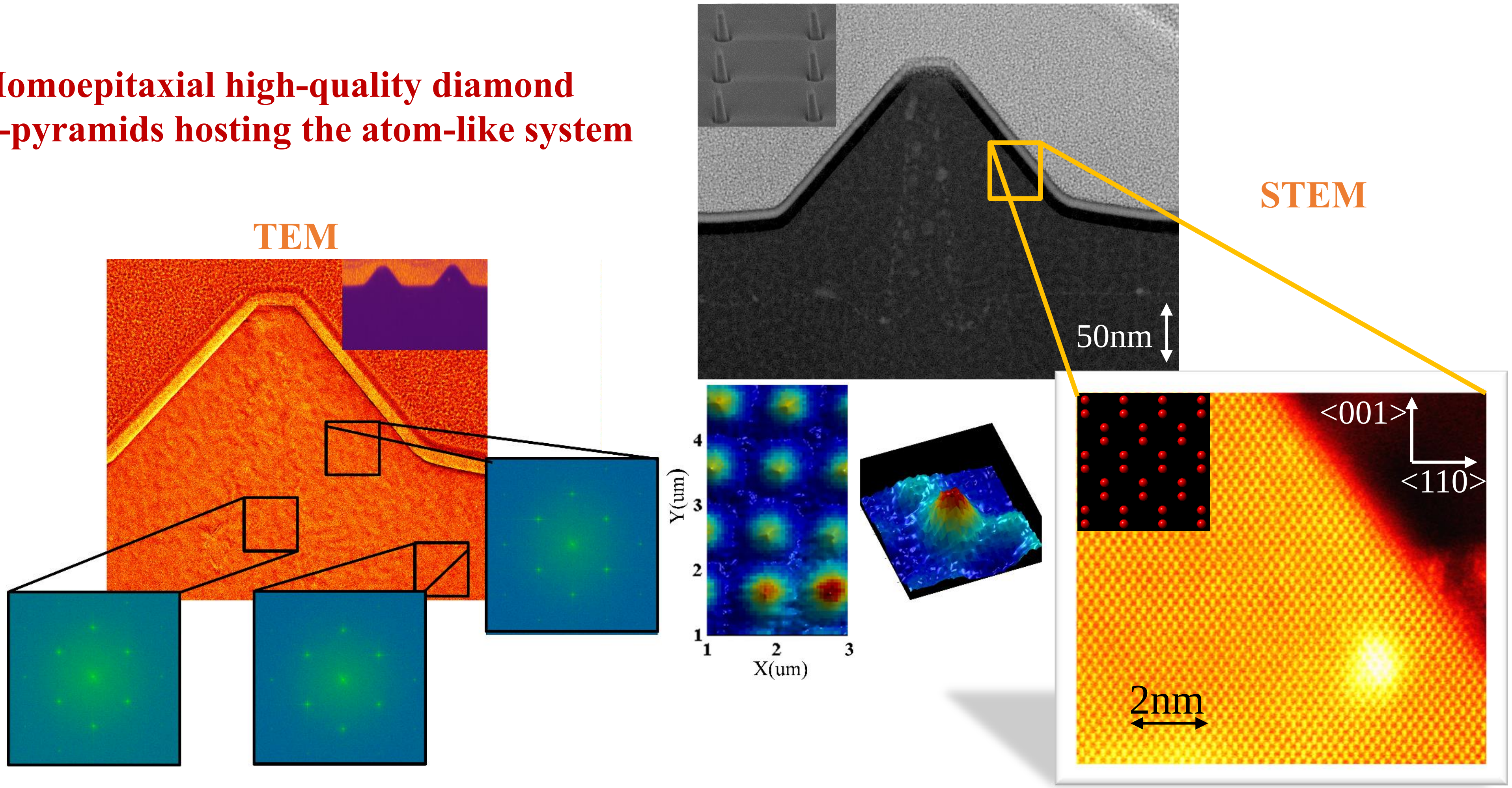




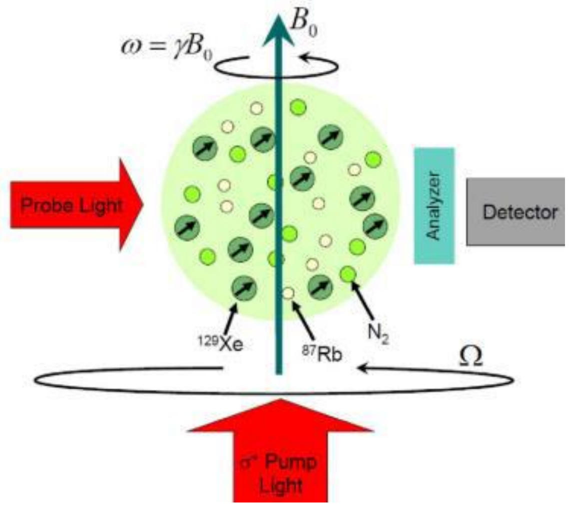


Epitaxially Grown *Diamond Nano-pyramids* Containing Embedded Quantum Sensors

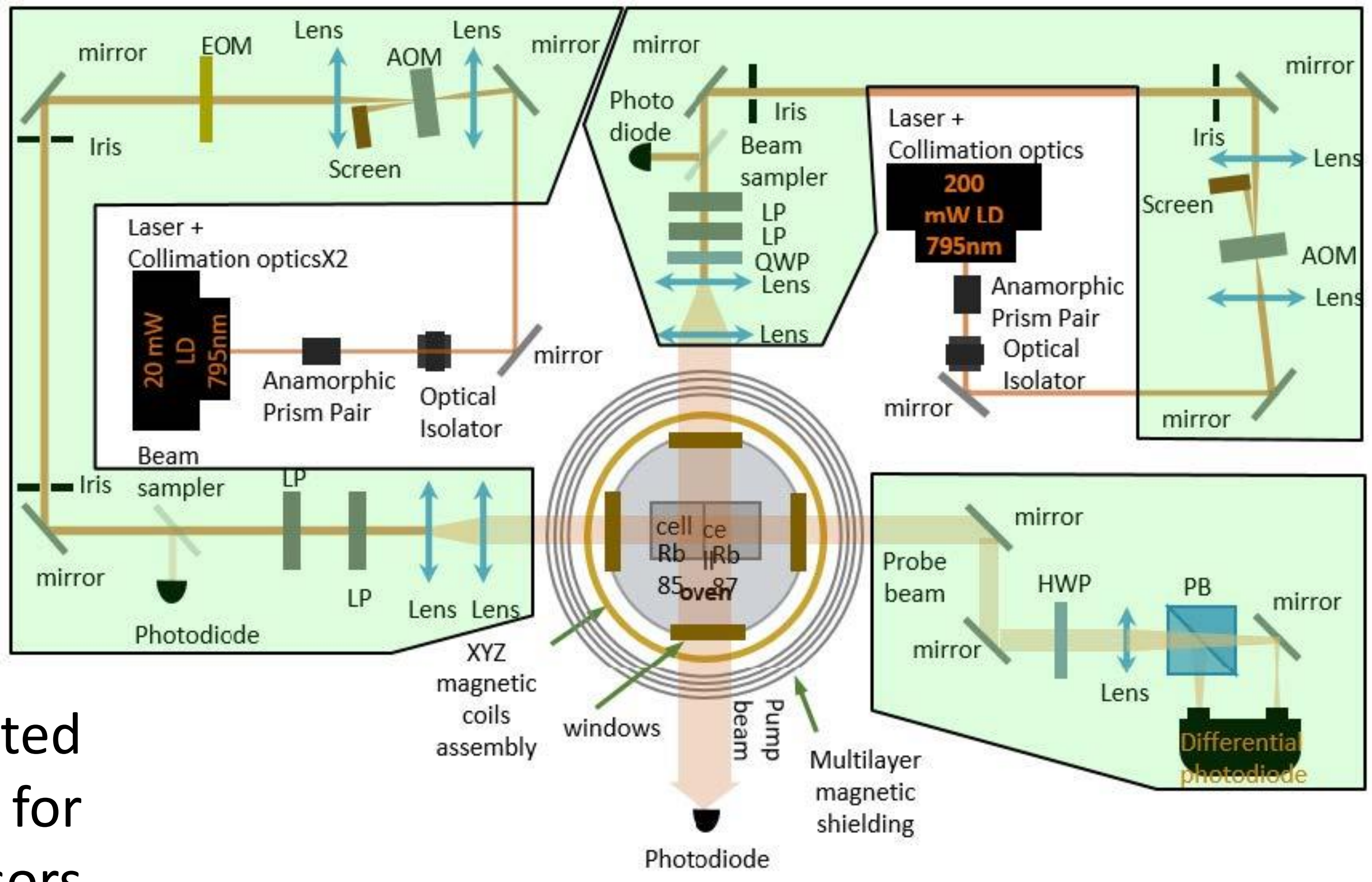
Homoepitaxial high-quality diamond nano-pyramids hosting the atom-like system



Miniature *Quantum Gyro*:
Quantum Silicon Photonics Technology



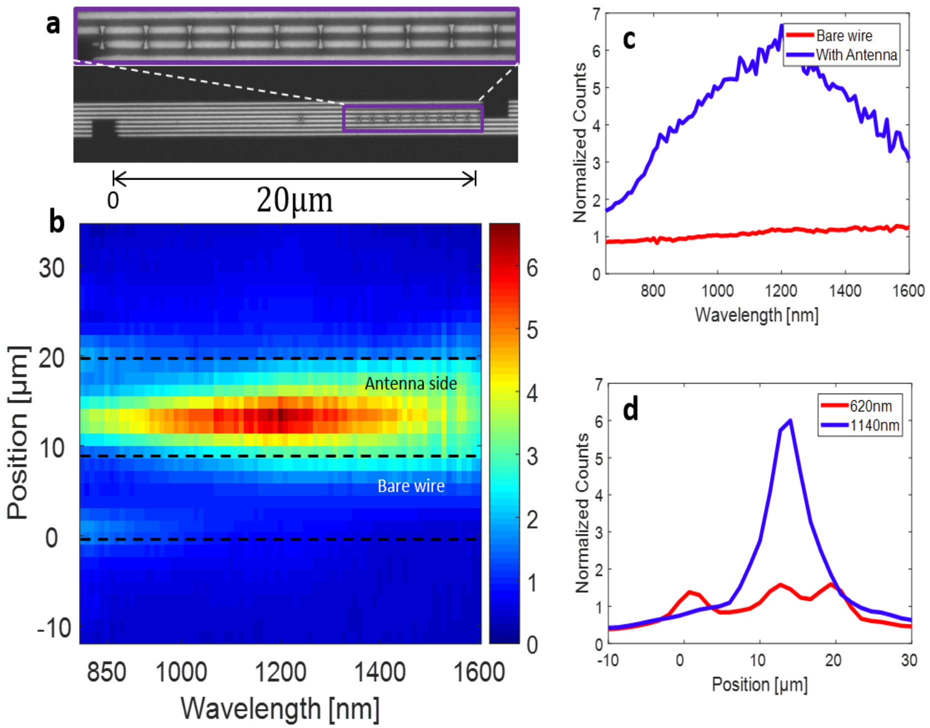
Measuring rotations with atoms

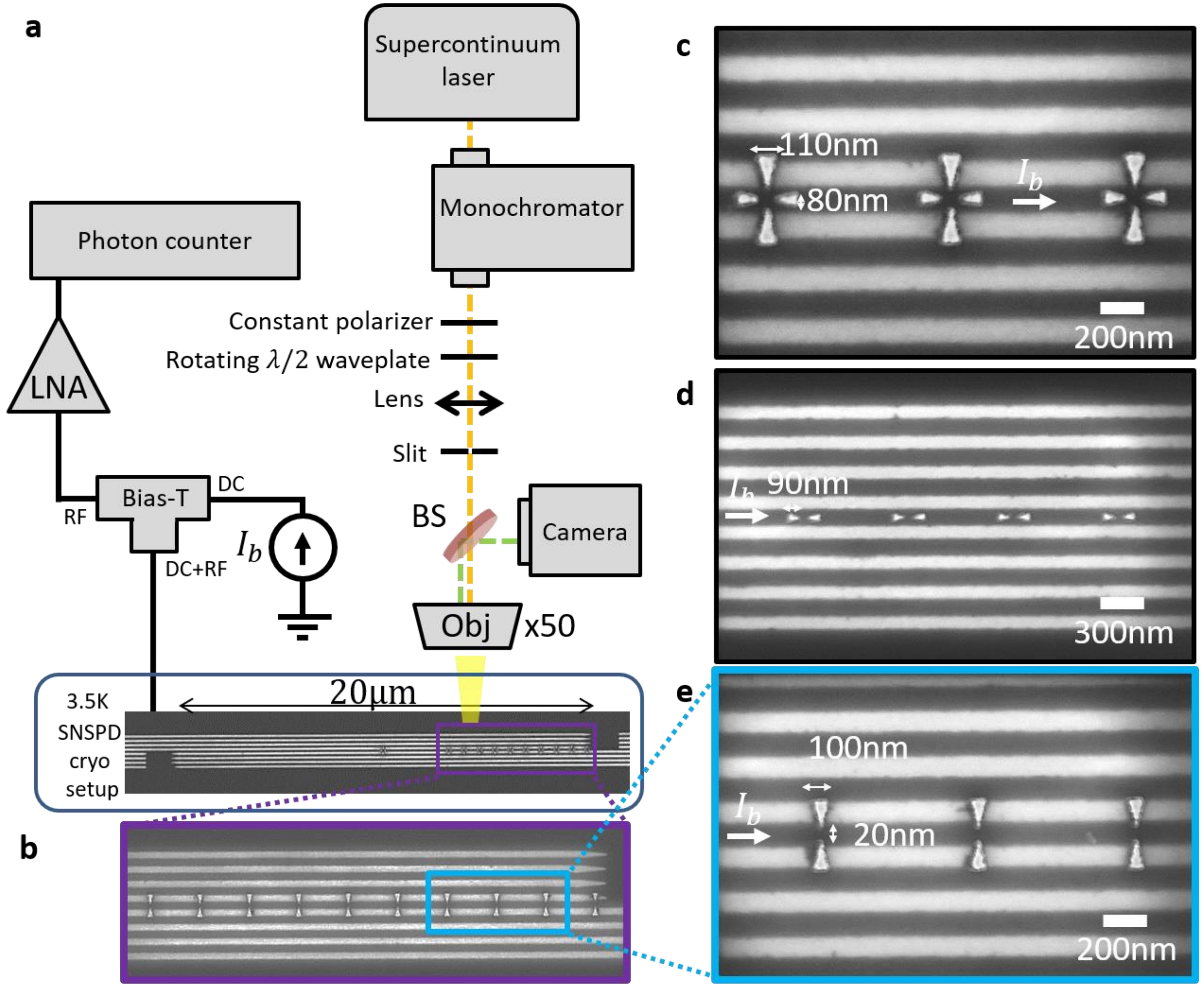


Development of Quantum-related "silicon-photonics" technologies for miniaturization of quantum-sensors

Collaboration with Rafael, Uriel (HUJI)

Enhancement of *Superconducting Nanowire Single Photon Detectors*: Polarized Plasmonic Nano-Antennas





Highest broad band enhanced responsivity was achieved.

Technion Technology Transfer

Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

Prof. Eyal Buks, Electrical Engineering

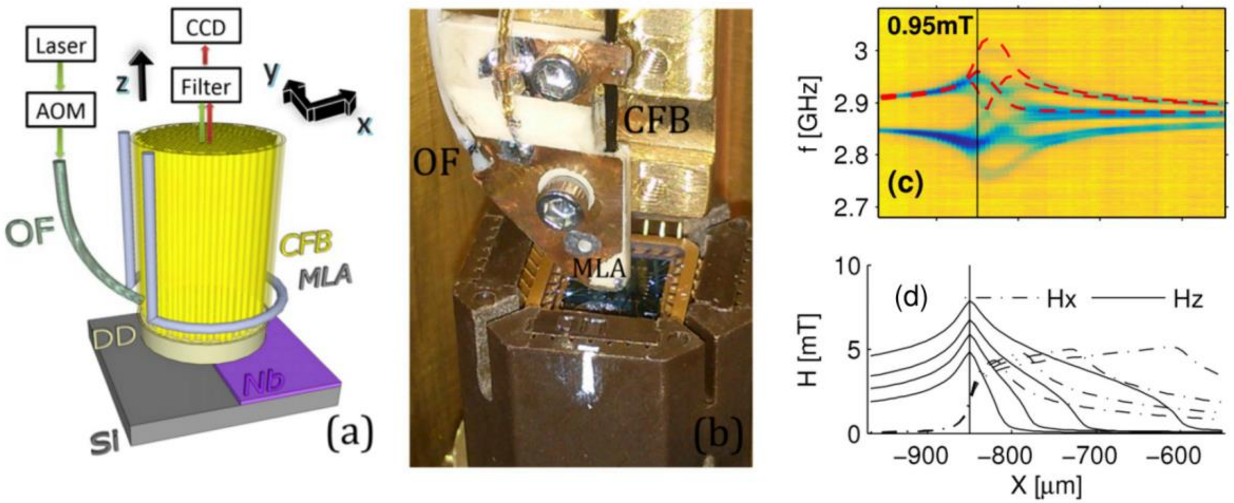
eyal@ee.technion.ac.il; 04 829 3450;

- Background of principal investigator – superconducting devices, MEMS, mesoscopic physics, diamond magnetometry
- Relevant activity – vector magnetometry with nitrogen vacancy defects in diamond

Potential collaborations

- Nir Bar-Gil (HUJI)
- Rafi Kalish (Technion)

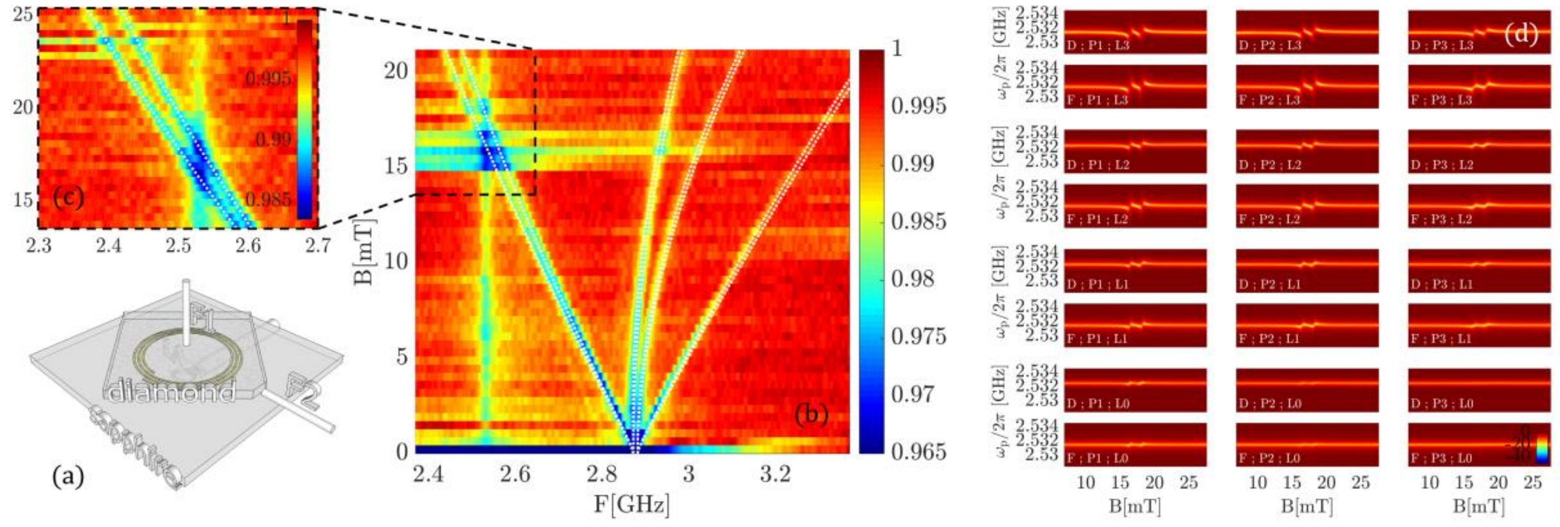
Our Cryogenic Diamond Magnetometer [1]



(a) The diamond disk (DD) containing NV defects is glued to the tip of a coherent fiber bundle (CFB) having 30,000 cores, and is brought to contact with the silicon (Si) wafer, which supports the superconducting niobium (Nb) film under study, using a 5-axis positioner. A room temperature optical setup allows optical imaging of the filtered ODMR signal using a charge-coupled device (CCD) camera. An optical fiber (OF) is employed for guiding the laser light into the CFB. Laser intensity is controlled using an acousto optic modulator (AOM). A microwave loop antenna (MLA) is used for applying alternating signals to the NV defects. (b) A photo of the magnetometer probing head and a sample under study. (c) Optically detected magnetic resonance (ODMR) measurements of the magnetic field generated by the shielding currents in the Nb stripe. (d) The corresponding theoretically predicted magnetic field.

[1] Diamond Magnetometry of Meissner Currents in a Superconducting Film
Nir Alfasi, Sergei Masis, Oleg Shtempeluk, Valleri Kochetok and Eyal Buks, AIP Advances **6**, 075311 (2016).

Diamond Coupled to a Superconducting Resonator [2]



(a) A loop antenna (LA) is coupled to the spiral resonator. Two multimode optical fibers are coupled to the diamond wafer. Fiber F1 is employed for delivering laser light of wavelength λ=532 nm, and fiber F2 probes the emitted PL. (b) The spiral resonator has 3 turns, an inner radius of 0.59 mm and an outer radius of 0.79 mm. (b) and (c) ODMR spectrum vs. driving frequency ω p /2π and magnetic field | B | . The white dotted lines represent the calculated ODMR frequencies. (d) Cavity mode reflectivity with various values of injected microwave power (P1 =−90 dBm, P2 =−70 dBm and P3 =−60 dBm) and laser intensity (L0 = 0, L1 = 5.6 mW/mm^2 , L2 = 12.8 mW/mm^2 and L3 = 30 mW/mm^2). For each pair the top plot is experimental data (labeled by D) and the bottom is the theoretical prediction (labeled by F).

[2] Nonlinear light-matter interaction in diamond
Nir Alfasi, Sergei Masis, Roni Winik, Demitry Farfurnik, Oleg Shtempluck, Nir Bar-Gill and Eyal Buks, arXiv:1711.07760.

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Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

Prof. Alex Hayat, Faculty of Electrical Engineering, Technion
alex.hayat@ee.technion.ac.il; +972-4-829-4682;

❖ Background of principal investigator:

- Global Scholar at Canadian Institute for Advanced Research (2013)
- Banting Postdoctoral Fellow, University of Toronto, (2011-2012)
- PhD, Technion, EE, Haifa, Israel (2011)
- Design Engineer - Intel, Haifa, Israel (2000-2005)

❖ Relevant activity –

- Development of low Tc (10K) superconducting optoelectronics
- Development of high-Tc (90K) superconducting optoelectronics
- Quantum metrology device development
- Ultrafast and quantum optics investigations

Technion Technology Transfer

High-Tc Superconducting Nanowire Single Photon Detectors (HT-SNSPDs)

-SNSPDs based on low-Tc superconductors are used in a variety of applications including:

- -Enhanced-sensitivity metrology
- -Quantum computing
- -Optical communications
- -Alpha, Beta and Gamma ray detection

-SNSPDs offer several key advantages such as:

- -High detection efficiency
- -Broad EM detection spectrum
- -Low dark count rates
- -Excellent time resolution, down to the pico-second range

-Main problem with existing devices: Low Tc superconductors require cooling to the ~10K

-Our solution: Development of high Tc superconductors with ~90K cooling

Proposed Research Directions

-High-Tc superconductors can operate well above liquid nitrogen temperature (77K)

-High-Tc based SNSPDs can thus result in a multitude of commercial applications

-Our proposed research direction:

-Design and demonstration of a High-Tc based SNSPD

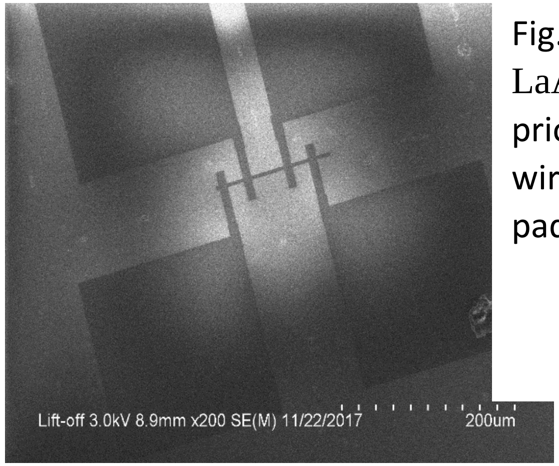


Fig. 1. An example of a SiN/ $LaAlO_3$ nanowire structure prior to YBCO deposition. The wire is in the center with 4 large pads around it for 4-probe tests

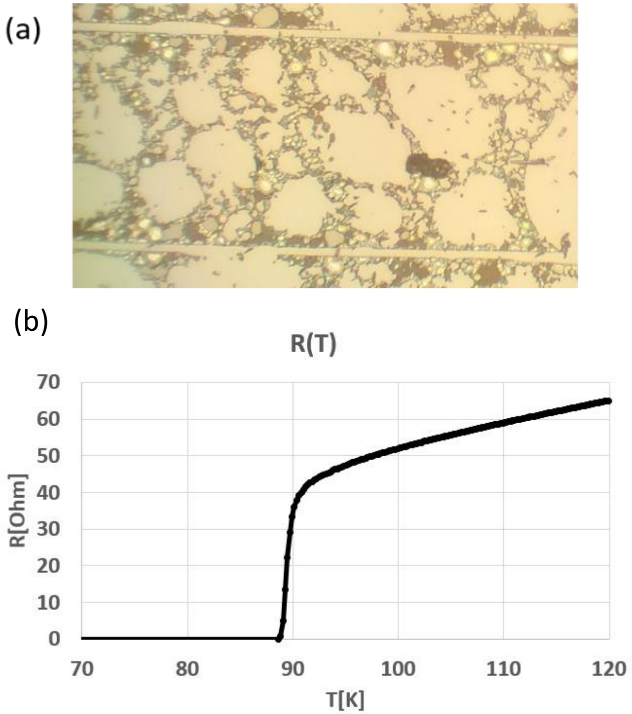


Fig. 2 (a) 2 Microwires fabricated using the selective growth method. The width of each wire is 8 μm and the spacing between them is 250 μm. (b) Tc measurement of the selectively grown microwires showing a transition around 87K.

-Potential collaborations:

-Prof. Amit Kanigel's group, which specializes in the growth of High-Tc superconductors

Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

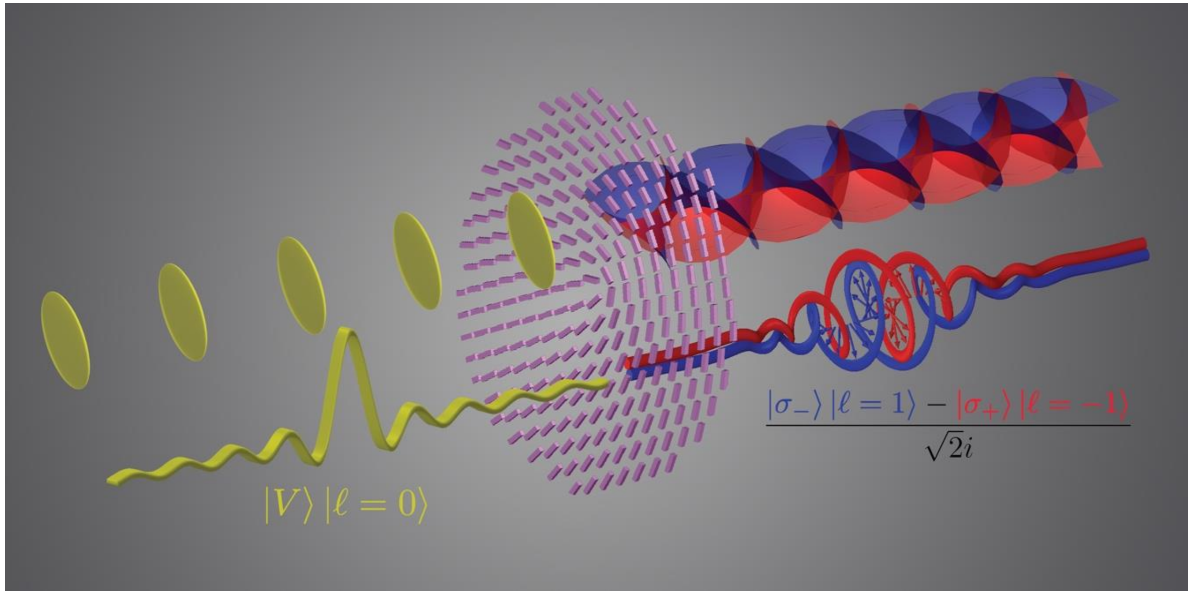
Quantum metamaterials: Generation, manipulation and sensing of photon entanglement

Prof. Erez Hasman, Faculty of Mechanical Engineering, and Russell Berrie Nanotechnology Institute

E-mail mehasman@technion.ac.il

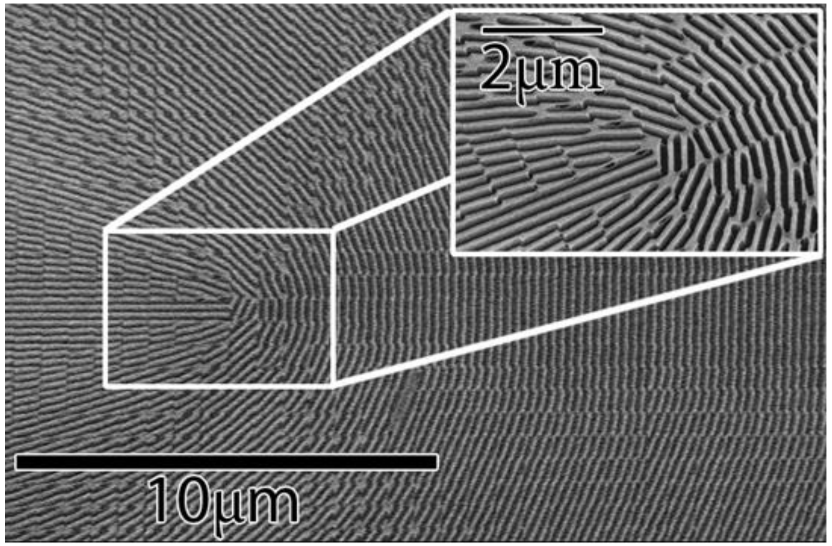
Prof. Mordechai Segev, Physics Department and Solid State Institute

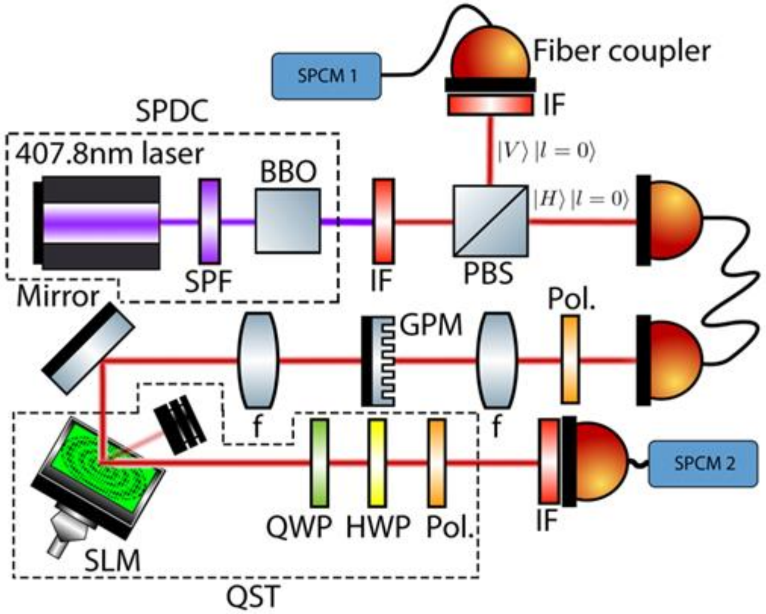
E-mail msegev@technion.ac.il



Quantum metamaterials: entanglement of spin and orbital angular momentum of a single photon

* The generation, manipulation and sensing of photon entanglement via quantum metamaterials provide the route for nano-photonic quantum information applications.
* We anticipate that metasurfaces will become a standard tool in future quantum optics, and will be used extensively in photonic quantum information systems.





Proposed Research Directions

- Generation of spin and orbital angular momentum entanglement using Silicon metasurface

- Manipulation of entangled states

- Sensing of photonic quantum states via interleaved Si metasurface (spin, angular momentum, entanglement..)

Technion Technology Transfer

Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

Prof. Yachin Ivry, Material Science and Engineering & Solid State

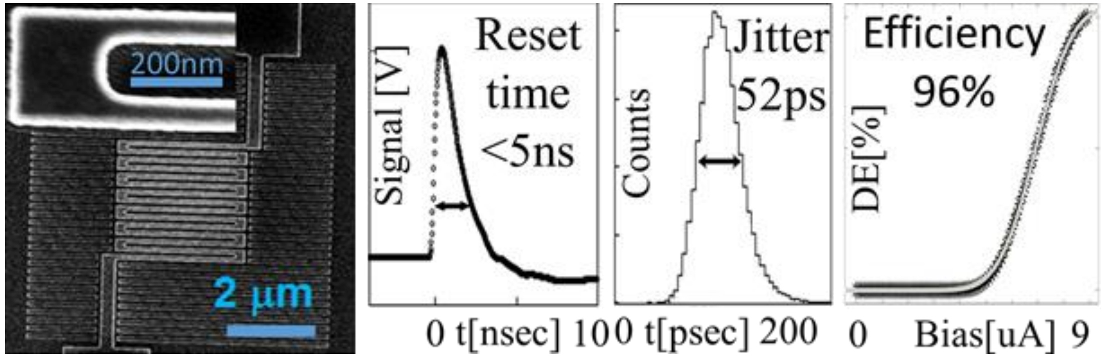
ivry@technion.ac.il; 04 829 4560;

- Background of principal investigator – quantum and piezoelectric sensors and detectors, microscopy, material processing, nanoscale characterization.
- Relevant activity – quantum devices for (i) ultra-sensitive magnetometry; (ii) efficient and ultra-fast IR detection, including single-photons; and (iii) processing high-quality quantum materials.

Potential collaborations

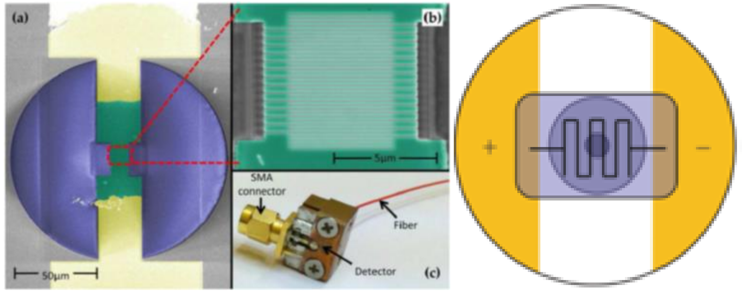
- Eyal Buks (Technion) – complementary experiments, PARTNER
- Emanuele Dalla Torre (BIU) - theory
- Hadar Steinberg (HUJI) – complementary experiments
- Karl Berggren (MIT) – complimentary system engineering

Fast and efficient single-photon detectors



Ultra-fast ($< 5[\text{ns}]$ deadtime and $< 55[\text{ps}]$ timing jitter) and efficient (96% quantum efficiency) single-photon detector (***UV to IR***). This technology is possible thanks to a novel approach of a bi-layer stack of $4[\text{nm}]$ thick superconducting material.

We wish to utilize this technology for quantum communication as well as to push this novel approach to allow single-photon sensing at the first and second atmospheric windows. On-chip.



Single-photon detector on fiber.

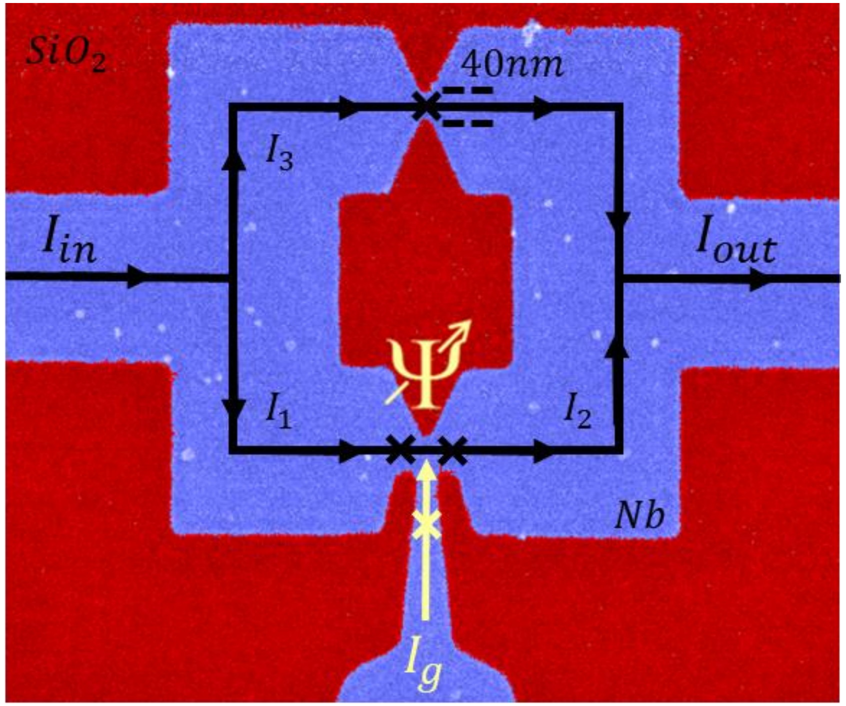
We wish to introduce novel materials for the detectors to allow high-efficiency on-fiber single-photon sensing. These detectors encompass the potential of being the most efficient single-photon detecting systems available.

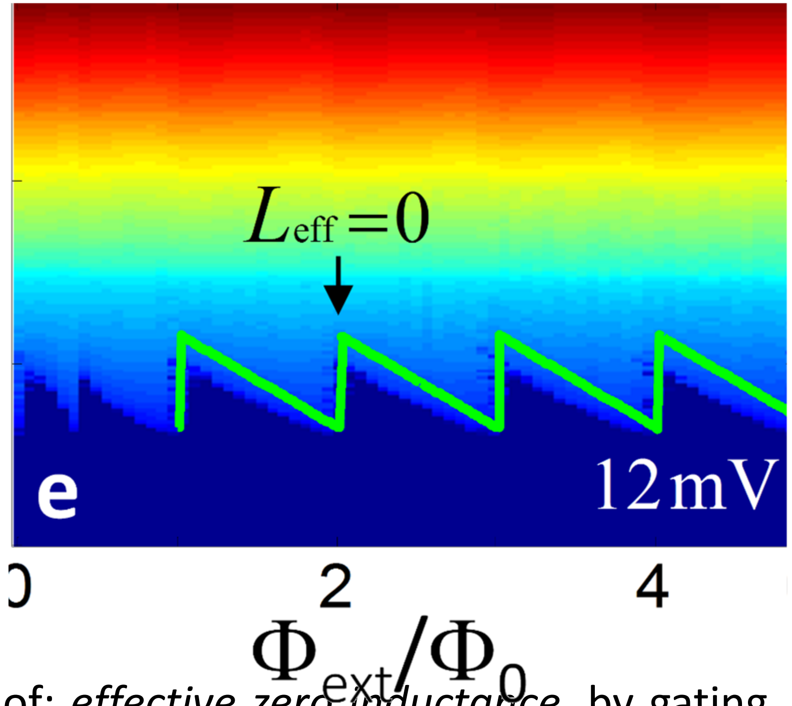
With Prof. Eyal Buks.

Ivry et al.: Nanotechnology **28** 43 (2017); Physical Review B **90** 214515 (2014); Applied Physics Letters **103** 142602 (2013); Frontiers in Optics 2013 **FW1C.5** (2013).

Buks et al.: Applied Physics Letters 101 **262601** (2012).

On-chip quantum devices for ultra-sensitive magnetic measurements and high-resolution spatial mapping & Quantum electronics





We recently demonstrated an unpredicted behavior of: *effective zero inductance*, by gating for the first time directly the weak-link in superconducting quantum interference devices (SQUIDs).

We are keen to realize the great technological potential of this novel discovery by utilizing the expected ultra-sensitivity to magnetic fields. Moreover, thanks to the unique geometry of our device, we can use its potential for high-spatial resolution mapping of magnetic fields.

Ivry, Buks et al.:Applied Physics Letters **112** 122601 (2018)

Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

Prof. Alon Hoffman, Schulich Faculty of Chemistry

choffman@tx.technion.ac.il   972 4 8293747

- Background of principal investigator -

Alon Hoffman holds the Joseph Szydlowsky Chair in Science. Since joining the Technion in 1992 has established a very visible research effort in the areas of surface science and thin films with strong activities in both basic and applied research. He has established three unique laboratories which are: a laboratory for deposition of diamond films by CVD methods; a laboratory for nano-microscopy (AFM and SCM); and a surface science laboratory with two unique ultra high vacuum systems equipped with state of the art surface analytical methods. His research effort spans from basic to fundamental research with more than 250 publication and more than 3000 citations making him a most prominent scientist in the field of diamond science and technology in Israel and world-wide.

During the last twenty five years his research has been related to different aspects associated to the chemical, physical and electronic properties of mainly diamond surfaces.   Particular emphasis was directed in his studes to the investigation of hydrogen, oxygen and nitrogen with diamond surfaces.   In addition he has investigated the different processes involved in the formation – nucleation and growth- of polycrystalline diamond films by chemical vapor deposition onto non-diamond substrates.

Of particular importance to the proposed research program is that prof Hoffman's group has recently proved the possibility of producing a nitrogen delta layer in the near surface region of diamond. The work has been published in APL.-

- Relevant activity –

Investigating the interaction of nitrogen with the surface and near surface region of single crystal diamond surfaces with the aim to form a delta doped nitrogen layer 1-2 nm thick and 4-5 nm below the diamond surface in which the nitrogen atoms populate NV- electronic structures in the near surface region of diamond.   This is necessary for the development of various applications related to quantum sensing using diamond as a quantum material.

Interaction of nitrogen with single crystal diamond surfaces and near surface regions for the creation of atomically sharp and nm shallow NV- centers for quantum sensing

A detailed understanding of the interaction of nitrogen with diamond surfaces and near surface region are most important in order to control its near surface electro-optical properties and the stabilization of NV- states in the near surface of diamond. Our research plan consist of three main parts:

(i) We will study the interaction of activated nitrogen with single crystal diamond surfaces;
(ii) We will investigate the possibility to create a delta nitrogen layer a few nm from the diamond surfaces; and
(iii) We will investigate different ways to activate the population of the NV- bonding state with the aim to create near surface and isolated NV- states necessary for quantum sensing application using diamond as a quantum material.

Proposed Research Directions

- We plan to investigate in-situ the interaction of activated nitrogen atoms with single crystal diamond surfaces with different crystallographic orientations (basically, on (100), (110) and (111)). The chemical bonding, its possible structure and electronic properties will be studied in-situ by various electron spectroscopic methods including XPS, UPS AES, TPD and HREELS. The structure of the nitrogen over layer will be investigated by LEED and STM.
- Then stage we plan to investigate the formation of near surface delta N-doping by in-situ nitrogen surface incorporation (as above) followed by diamond growth by CVD. The CVD process will be carried out both by the hot filaments and microwave activation methods.
- Finally we will investigate ways to stabilize the bonding configuration of the incorporated atomic nitrogen in the near surface region of diamond in the NV- configuration. This will be achieved by examine different surface chemical terminations (i.e. Hydrogen, Oxygen, Fluor, Nitrogen) or by inducing a near surface n-doping which will result in surface band bending which may promote the NV- population.
- **The expected significance** is the successful formation of a delta doped nitrogen layer 1-2 nm thick and 4-5 nm below the diamond in which the nitrogen atoms populate NV- electronic structures in the near surface region of diamond. This is necessary for the development of quantum sensing applications using diamond as a quantum material.

Potential collaborations

- ICDAT, Israel center for advance diamond technologies, Nesher, Haifa.
- Rafael
- Prof Nir Bar Gil, Racah Institute of Physics, Hebrew University, Jerusalem.

Proposal for

מאגד לפיתוח טכנולוגיות בתחום חישה קוונטית

Prof. Aharon Blank, Schulich Faculty of Chemistry

ab359@technion.ac.il; 04-8293679;

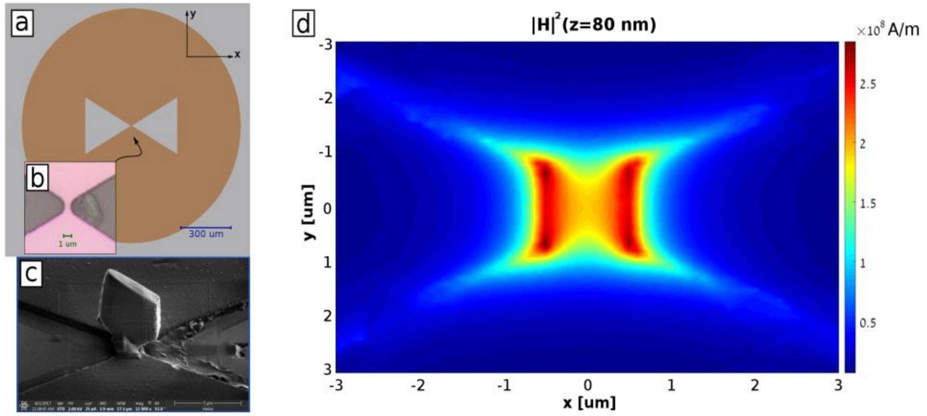
- **Background of principal investigator:** The lab of A. Blank focuses on the development and applications of new methodologies in the field of magnetic resonance. This ranges from fundamental issues such as detection of small number of spins at nanometer-scale resolution, to more applied aspects, such as development of compact magnetic resonance probeheads for clinical applications.
- **Relevant activity:** Electron spins, controlled and detected by a variety of magnetic resonance techniques, can be used as sensitive sensors for magnetic fields. We are development methods to manipulate electron spins and detect them by induction detection, as well as optical and electrical detection schemes.

Technion Technology Transfer

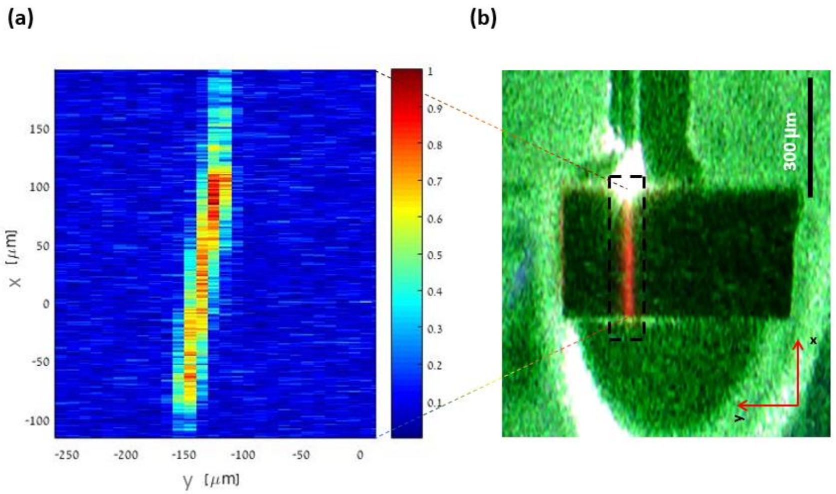
Quantum Technologies at the lab of A. Blank, Chemistry, Technion

- Development of miniature ultra-sensitive resonators aimed at the induction detection of single electron spins.[1]
- Imaging and selective addressing of spins of NV centers in diamond by MRI methods (with magnetic field gradients), using optical detection with resolution below the diffraction limit. [2]
- Development of methodologies for sensing and imaging of electron spins for structural biology by indirect NV detection.[3]

Miniature resonators for induction detection of single spins[1]



MRI of NV centers in diamond[2]



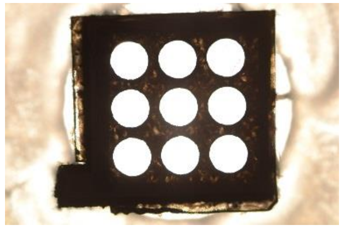
[1] Applied Physics Letters 106, (2015) 084104

[2] European Physics Letters, 117 (2017), 1001

[3] Physica Status Solidi (a), 253, (2016), 1167–1176

Proposed Research Directions

- Development of vibration and acceleration sensors based on measuring the position of NV centers on diamond membrane



- Development of 3D magnetic field imager
- Development of tools for molecular structure determination
- Progress towards spin-based quantum computing

Potential collaborations

❖ ICADT – Developing the diamond membranes

❖ Rafael – developing NV-based sensors

Technion Technology Transfer

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