Quantum optics with GeV color center in diamond

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Integrated nanophotonics – next step in Information processing

Photons:
• Have no ohmical losses
• Have huge carries frequencies
• IBM already trying to use photonics for processor interconnects

But...
Wide use require new platforms for photon switching and processing

Quantum communication:
• Offers new security level
• Exists on market as short range solution
• Need quantum repeaters for long distance

NEED TO INTEGRATE LIGHT AND MATTER ON QUANTUM LEVEL
Color centers in diamond at glance

Problems:
- Polar structure – large sensitivity to electric field – sensitive to defects in nanostructure
- Broad spectrum with only 5% in zero-phonon line – bad for photonics applications

Advantages:
- Symmetric structure – not sensitive to external fields
- Strong zero-phonon line
  But
- Decay of excited state is mostly non-radiative

Well developed and have many potential applications


Advantages:
- Symmetric structure – not sensitive to external fields
- Strong zero-phonon line
- Radiative decay only
GeV center, the spectra

- Spin ½ system with 0 orbital moment
- Narrow zero-phonon line around 602 nm dominating the spectra even at room temperature
- $\Lambda$-scheme available
- Phonon sideband enable resonance spectroscopy
How to absorb one photon with atom?

✓ Single photon - single atom interaction probability: \[ \sim \frac{\lambda^2}{d^2} F \]

transverse localization
Strong optical coupling at the nanoscale

Coupling strength: \[ g = \frac{\vec{d} \cdot \vec{E}}{\hbar} \]

Electric field of a single photon: \[ E = \sqrt{\frac{2\hbar \omega}{\varepsilon_0 V}} \]

**Mode volume** \((V)\) is the key parameter for increasing the coupling strength \(g\) so cooperativity is:

\[ \eta = \frac{(2g)^2}{\kappa \gamma} \quad \Rightarrow \quad \eta = \frac{3}{4\pi^2} \left( \frac{\lambda_0}{n} \right)^3 \frac{Q}{V} \sim \frac{\lambda^3}{V} Q \]

Atom-photon coupling can be enhanced with optical cavity
Possible realisations of strong optical coupling at the nanoscale

**Fabry-Perot**

Kimble, Rempe, ...

- $V \sim 10^5 \lambda^3$
- $Q \sim 10^7$

**Microtoroids**


- $V \sim 10 - 10^3 \lambda^3$
- $Q \sim 10^8 - 10^9$

**Photonic crystals**

- $V \sim 1\lambda^3$
- $Q \sim 10^4 - 10^5$

**Plasmonics**

Akimov ... Lukin (2007) $g = d$

- $V < 0.01\lambda^3$
- $Q \sim 1 - 10^2$
Photonic crystals
Photonic crystal cavities for diamond color centers

NV in diamond based cavities:
• **Pluses:**
  • Color center could be implanted in diamond directly

• **Problems:**
  • NV center is too sensitive to damage during fabrication
  • NV spectra is too broad – need to be overcome with Q
  • Diamond cavity are hard to fabricate, Q is not that high

SiV in diamond based cavities – it is not sensitive to damages!
• **Problems:**
  • Too much of non-radiative decay
  • Diamond cavity are hard to fabricate, Q is not that high

Many other groups in the field:
• Mikhail Lukin
• Marko Loncar
• Englund Dirk
• Raymond G. Beausoleil
• Christoph Becher
• Fedor Jelezko
• Jean-François Roch
• and many others...

Harvard University: Lukin, Loncar groups


*Science*, 2016, 354(6314), pp. 847-850
Idea: combine ultra-small GeV and high Q photonic crystal cavities

GeV^− advantages:
• No non-radiative decay
• Not sensitive to damages
• Could be created in ultra small crystals

Idea: We can try to combine ultra small GeV with non-diamond high Q- cavities

Problems:
• Need good nanodiamonds with GeV → Collaboration with diamond growing groups (Novosibirsk, Troizk, TAMU)
• Need good cavity → Collaboration with good fabrication groups (Germany, USA)
• Need diamond positioning → we have it!
Positioning of nanodiamonds: the technology

Esteban Bermudez-Uren et al, Nature Communications 2015

Cover slips Menzel-Glasser 130-160 μm, 18x18 mm

Aluminum

Resist PMMA 3%

«Glue» (poly) diallyldimethylammonium

Nanodiamonds solution, ~100nm used so far...
Work in progress

- First cavities
- Diamonds to be placed
Sensors

GeV happened to be not sensitive to the environment, right?
Diamond Thermometry – why?

• Temperature regulates many processes inside the cell
• Lack of in-cell thermometers

Recent proposal:
• NV based thermometer
  • Diamond is chemically inert
  • Record resolution down to 1 mK
  • May be also realized in fiber version
• But it requires strong microwave field

Can we do all - optical biocompatible thermometer?

Nature 2013, 500, 54–58

Sci. Rep. 2015, 5, 15737
Thermometry

Idea:
- Position and width of GeV depends on temperature
- We can measure temperature by measuring GeV Spectra!
- It is fully optical technique, no microwave involved
- Minimal production of phonons
Approximation of the Spectra

Idea:
• Spectra is complex, has many small features
• Fit need to be robust
• Minimal number of Lorencians capturing main features at room temperature is 3
• Below 150 K one need 4.
Electron-Phonon interaction

Model:
- Electron-phonon interaction cause rapid transitions between two excited states of GeV center
- Shift of Excited state $\Delta E \sim T^3$
- Transition width $w \sim T^3$
Checking lower temperatures...

A Boltzmann distribution establishes faster, then spontaneous decay. At low temperatures, the relative weight of two excited states should be corrected by:

\[ n_+ / n_- = \frac{\Delta E}{kT} \]

With Boltzmann factor included, the position follows a cubic law as well.
Thermometry resolution

- Resolution of thermometry achieved is below 0.1 K
- Approximately $10^3$ color center leading to $10^7$ counts/second
- Sensitivity is 300 mK/$\sqrt{\text{Hz}}$
Short noise limited performance

- Experimental spectrum integrated over several minutes at stable temperature
- It was fitted with 3 Lorentzian curves
- Resulting contour was used as distribution for random spectrum simulations.
- Large sample with 4000 realizations
- In experiment only 200 second were taken, so 200 realizations reproduces experiment, even oscillations!
Fiber Probe

- Smaller NA of the fiber (0.12 versus .95)
- Larger collection volume
- Essentially no loss
- Same level of sensitivity

- Sensitivity could be considerably improved by using high NA fiber
SnV – next in the table

- Less color centers
- More susceptibility
- Same level of sensitivity/color center

<table>
<thead>
<tr>
<th>Color center in diamond</th>
<th>Temperature susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin-vacancy (SnV)</td>
<td>0.0141 nm/K (11 GHz/K)</td>
</tr>
<tr>
<td>Silicon-vacancy (SiV)</td>
<td>0.012 nm/K (6.8 GHz/K)</td>
</tr>
<tr>
<td>Germanium-vacancy (GeV)</td>
<td>0.009 nm/K (6.8 GHz/K)</td>
</tr>
</tbody>
</table>

Sensitivity = \(500 \text{ mK}/\sqrt{\text{Hz}}\)
Outlook

• Implementation of quantum memories

• Application to in-cell temperature detection

• Strong coupling of GeV in nanodiamond to 1D fiber integrated structures

• Single photon nonlinear optics, switches, transistors
Team and collaborators

The team:

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Collaborators:

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Diamonds growing:
HPP RAS, Russia  Valery Davydov;
Sobolev Institute RAS, Russia: Yuri N. Palyanov, Yuri M. Borz dov
Thank you for your attention!