Superconductivity in Nanodiamond

NANO-SCALE TRANSPORT PHYSICS LABORATORY

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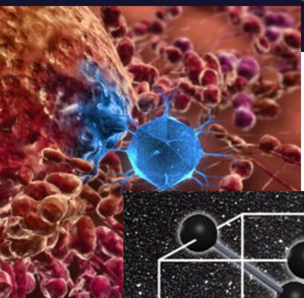
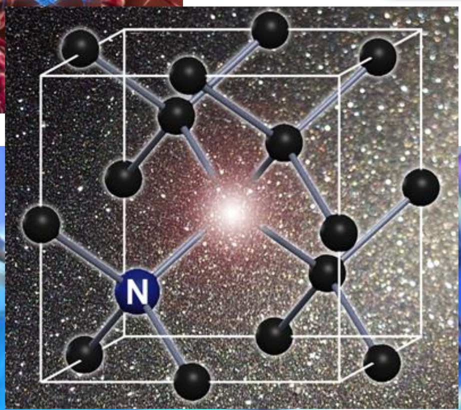
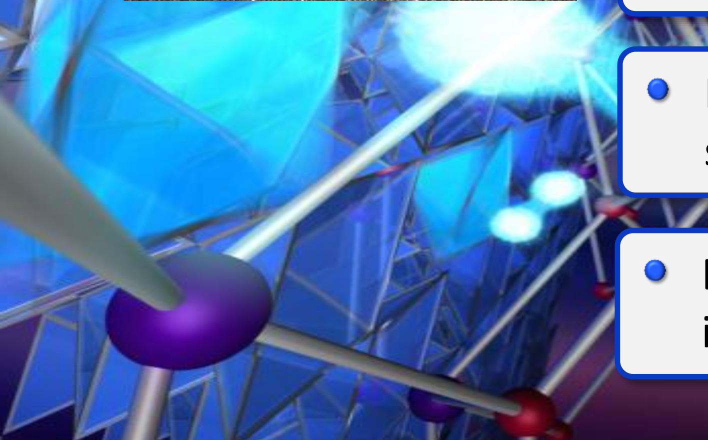
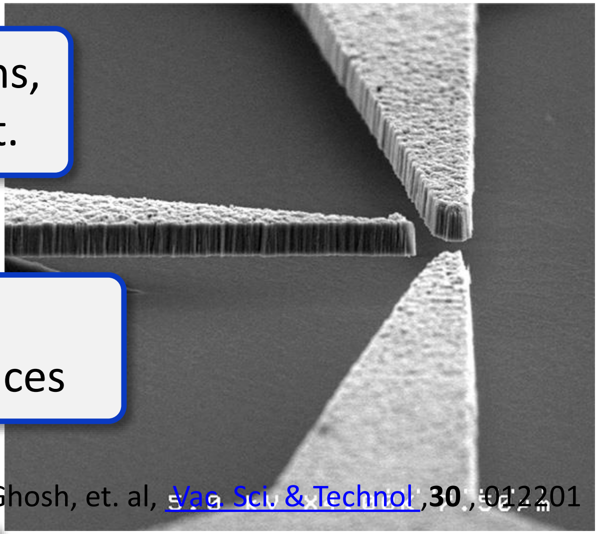
Nanodiamond





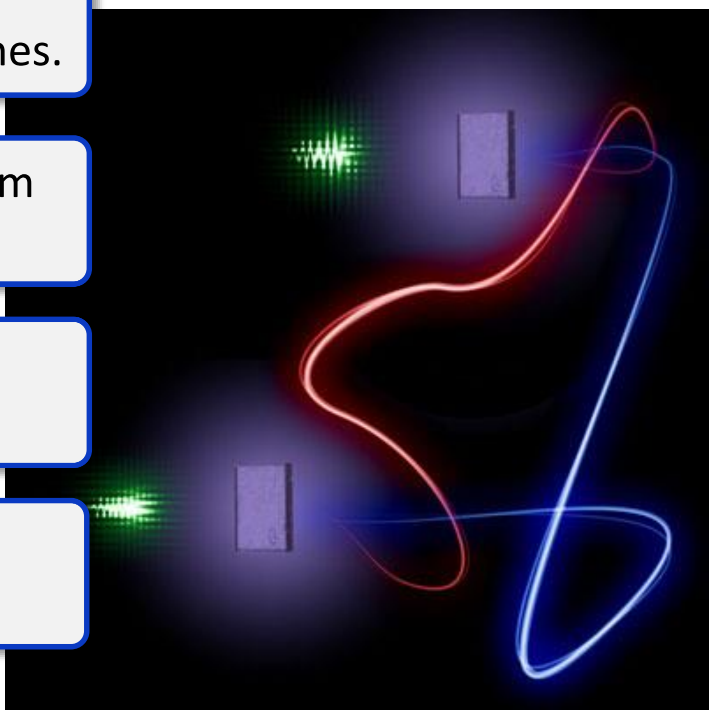


- Widespread biomedical applications, from medical imaging to treatment.
- Excellent thermal transfer, robust low power electronics, field emission devices



Ghosh, et. al, Vac. Sci. & Technol ,**30** , 012201

- Quantum information, exceptional coherence times.
- Phonons entangled at room temperature in diamond.
- New class of superconducting devices?
- B-NCD covalent SC with interesting microstructure

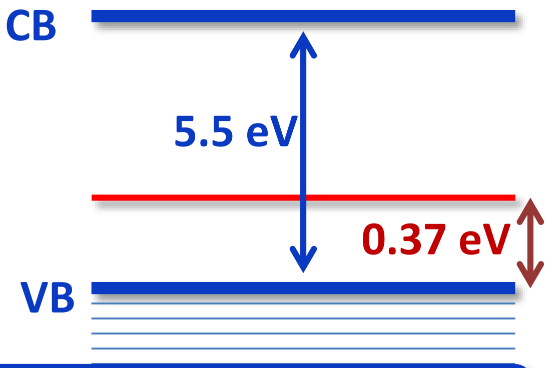


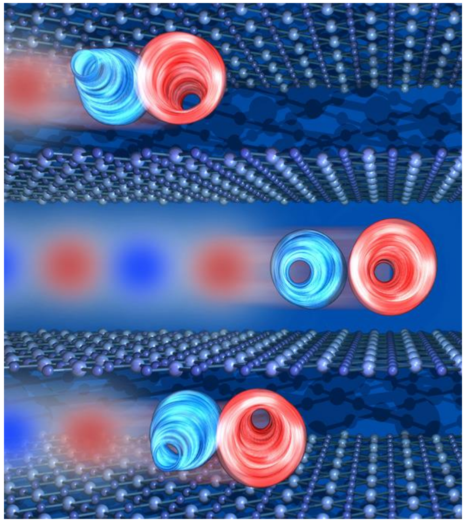
Superconductivity in Nanodiamond

- Diamond, intrinsically a high bandgap semiconductor (5.5 eV). Boron substitutionally incorporated. Diamond has highest Debye temperature, ~2 300 K.

- Creates deep, narrow impurity acceptor band 0.37 eV above the valence band.

- Difficult to dope, high structural integrity. Hence doping **introduces disorder**. Superconductivity, T_c high as 10 K.





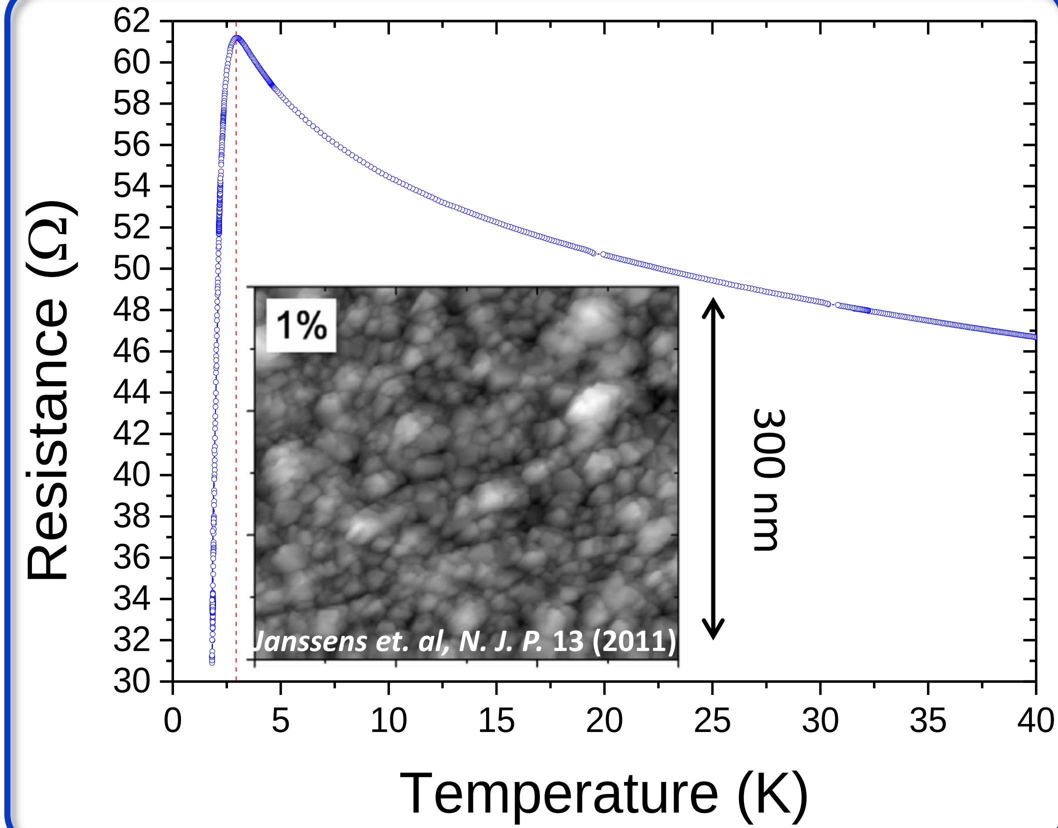
- Experiments show Anderson-Mott insulator to metal transition, evidence of non-rigid impurity band states.

- Experimental work in BNCD needed to interpret grain boundary effects. **Vortices** not yet studied.

- Theoretical work needed to interpret the **role of disorder** in BNCD.

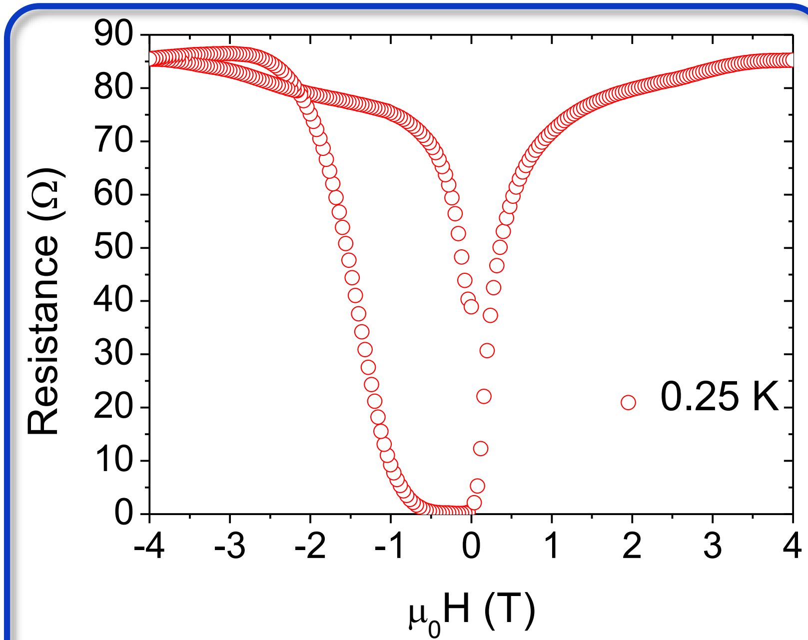
- We present tandem experimental and theoretical work towards understanding superconductivity in BNCD, focusing on the influence of disorder. Studies samples with different boron concentrations and microstructures.

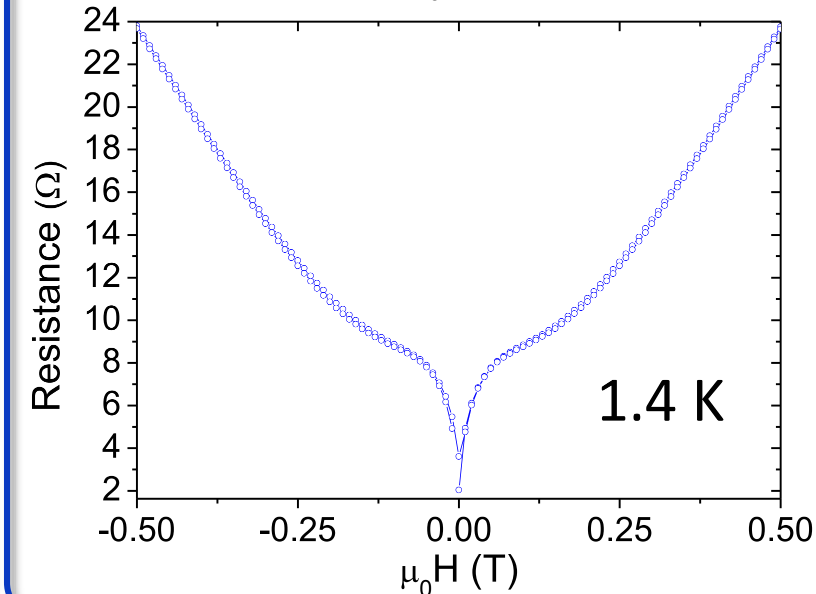
1 % H_2 BNCD



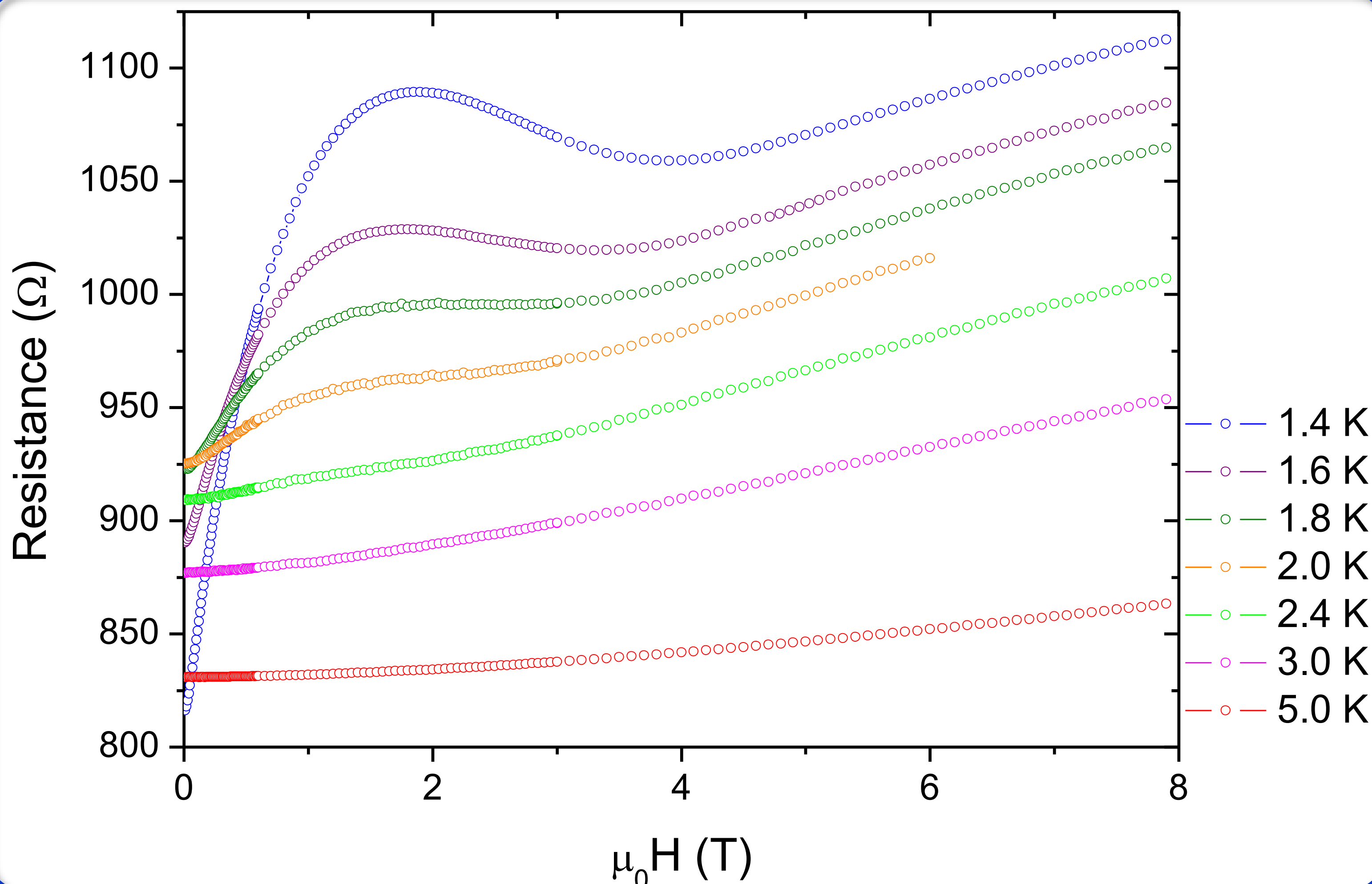
Transport measurements on boron doped nanodiamond, atomic B concentration 2.8 x 10^{21} cm^{-3}, > Mott trans. Grain size 50 – 70 nm. T_{on} 3 K.

MR at 0.25 K shows significant hysteresis. Characteristic of type II SC.





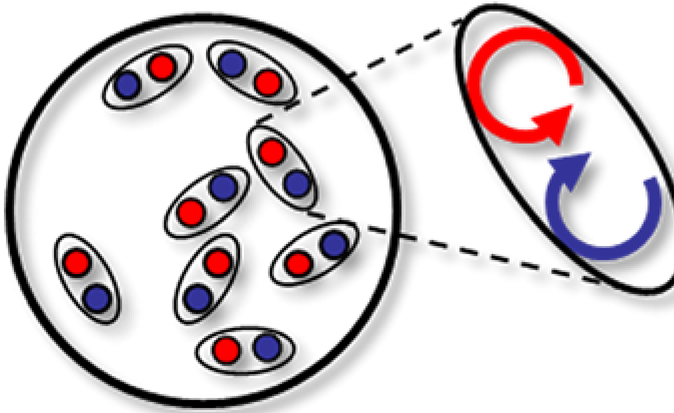
5 % H_2 BNCD



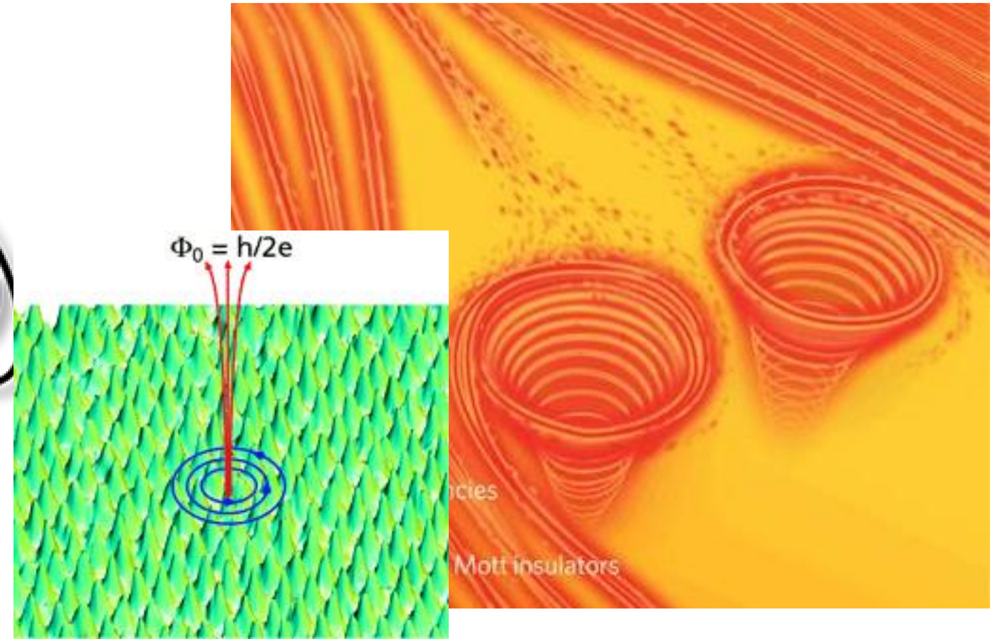
- Region of negative MR decreases with temperature, vanishes around 2.4 K (just above the metal-insulator transition).
- Gradient of MR in high field region changes little in temperature range. Characteristic of disordered metal.

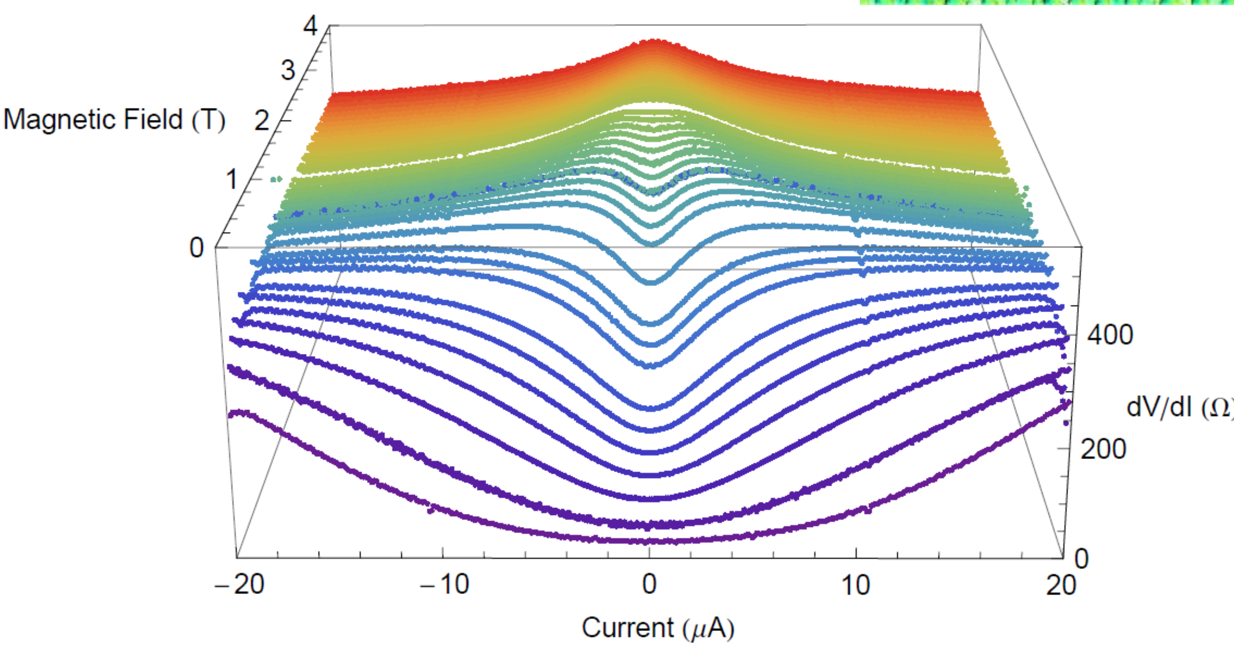
5 % H_2 BNCD

Superfluid ($T < T_C$)



Bound vortex-antivortex pairs





- In **strictly** 2D type II superconductors, vortex-antivortex pairs decouple (known as BKT transition in analogy with X-Y model.)

Inhomogeneous Mean Field Bogoliubov-de Gennes Study

- Study boron-doped diamond using the inhomogeneous Bogoliubov de-Gennes theory within a mean-field approximation.
- Boron doping forms narrow boron acceptor band in diamond. Degeneracy lifted by inhomogeneity.

- Treat single narrow boron acceptor band, therefore include Coulomb interaction. Mean field Hamiltonian:

$$\mathcal{H} = \sum_{i,\sigma}(\epsilon_i - \mu_i)c^\dagger_{i\sigma}c_{i\sigma} + \sum_i(\Delta(r_i)c^\dagger_{i\uparrow}c^\dagger_{i\downarrow} + \Delta^*(r_i)c_{i\downarrow}c_{i\uparrow}) - t_{i,j}\sum_{\langle i,j\rangle,\sigma}(c^\dagger_{i\sigma}c_{j\sigma} + h.c.) + \sum_{\langle i,j\rangle} W_{i,j}(n_i n_j),$$

- Hamiltonian rendered diagonalizable through Bogoliubov-Valatin transformation of the Fermion operators

$$c_{i\sigma}(r_i) = \sum_{i,\sigma} u_{n\sigma\sigma'}(r_i)\gamma_{n\sigma'} + v^*_{n\sigma\sigma'}(r_i)\gamma^\dagger_{n\sigma'}$$

Inhomogeneous Mean Field Bogoliubov-de Gennes Study

- The resulting matrix equation is of the form:

$$\begin{pmatrix} H_{BdG} & \Delta \\ \Delta^* & H^*_{BdG} \end{pmatrix} \begin{pmatrix} u_{n\sigma}(r_i) \\ v_{n\sigma}(r_i) \end{pmatrix} = E_n \begin{pmatrix} u_{n\sigma}(r_i) \\ v_{n\sigma}(r_i) \end{pmatrix}$$

- The pairing amplitude can then be expressed in terms of the Bogoliubov operators as:

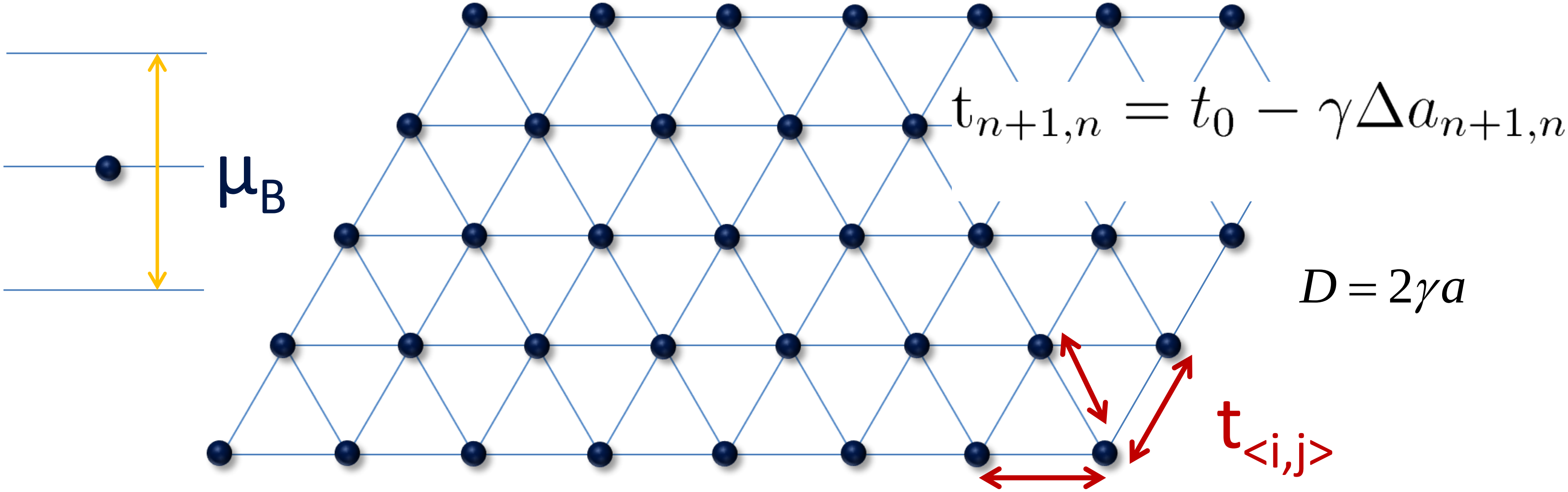
$$\begin{aligned} \Delta(r_i) = \quad & V \sum_n u_{n\uparrow}(r_i) v^*_{n\downarrow}(r_i)[1 - f(E_n)] \\ & + u_{n\downarrow}(r_i) v^*_{n\uparrow}(r_i) f(E_n), \end{aligned}$$

- In this representation, the occupation number is

$$n(r_i) = \sum_n |u_{n\uparrow}(r_i)|^2 f(E_n) + |v_{n\uparrow}(r_i)|^2 (1 - f(E_n))$$

- The system is solved self-consistently by updating the eigenvalues and iterating.

Inhomogeneous Mean Field Bogoliubov-de Gennes Study



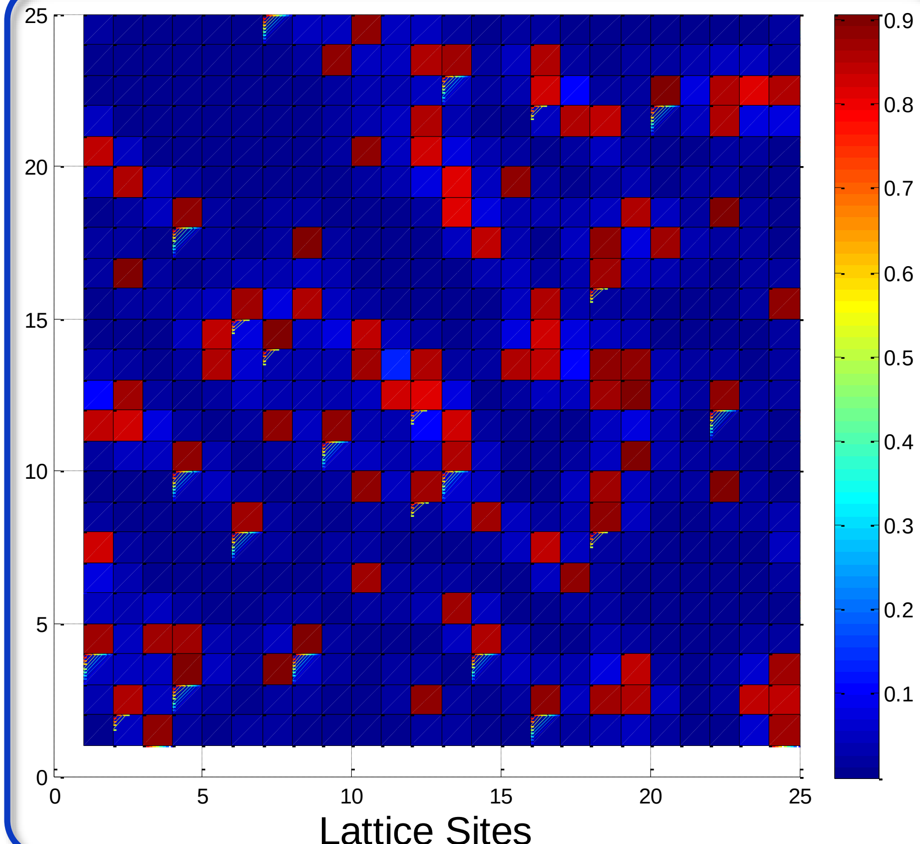
On-site Disorder

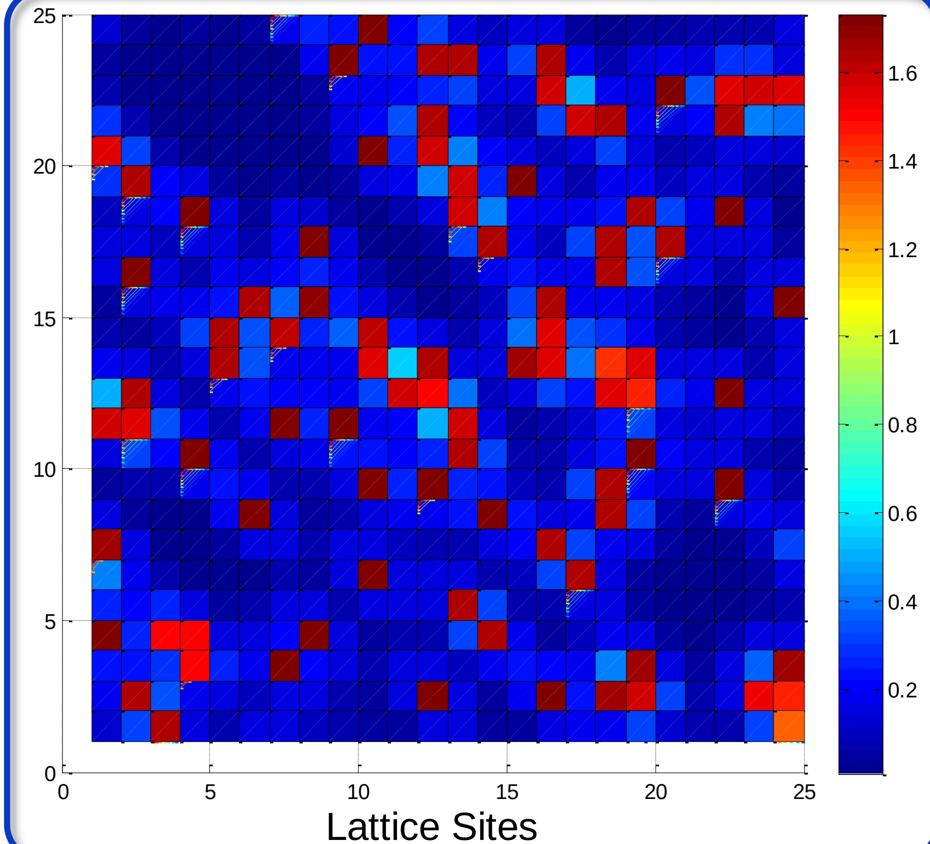
- Shift in the local chemical potential of the boron sites (diagonal disorder).
- Chemical potential of boron sites assumed to follow Gaussian distribution about self-consistently determined chemical potential of boron sites.
- Disorder parameter defined as the FWHM of the Gaussian.

Structural Disorder

- Inhomogeneous hopping parameter between all sites (non-diagonal disorder), represents bond-length disorder.
- Hopping parameter assumed to follow Gaussian distribution about some mean value.
- Disorder parameter defined as the FWHM of the Gaussian.

Inhomogeneous Mean Field Bogoliubov-de Gennes Study





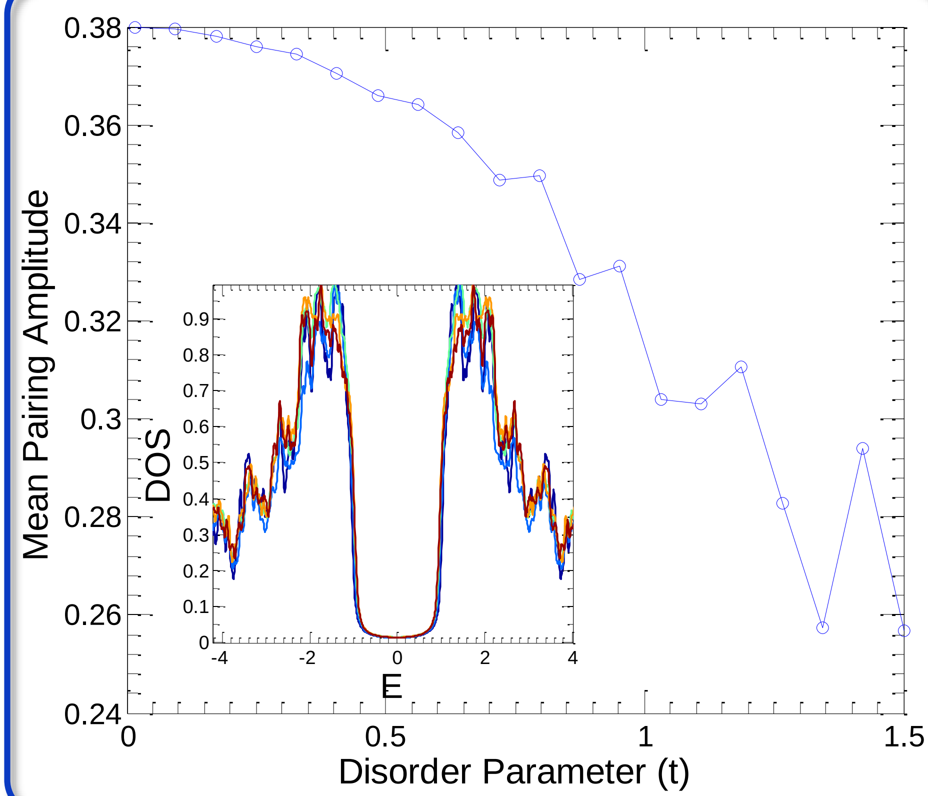
Occupation Number

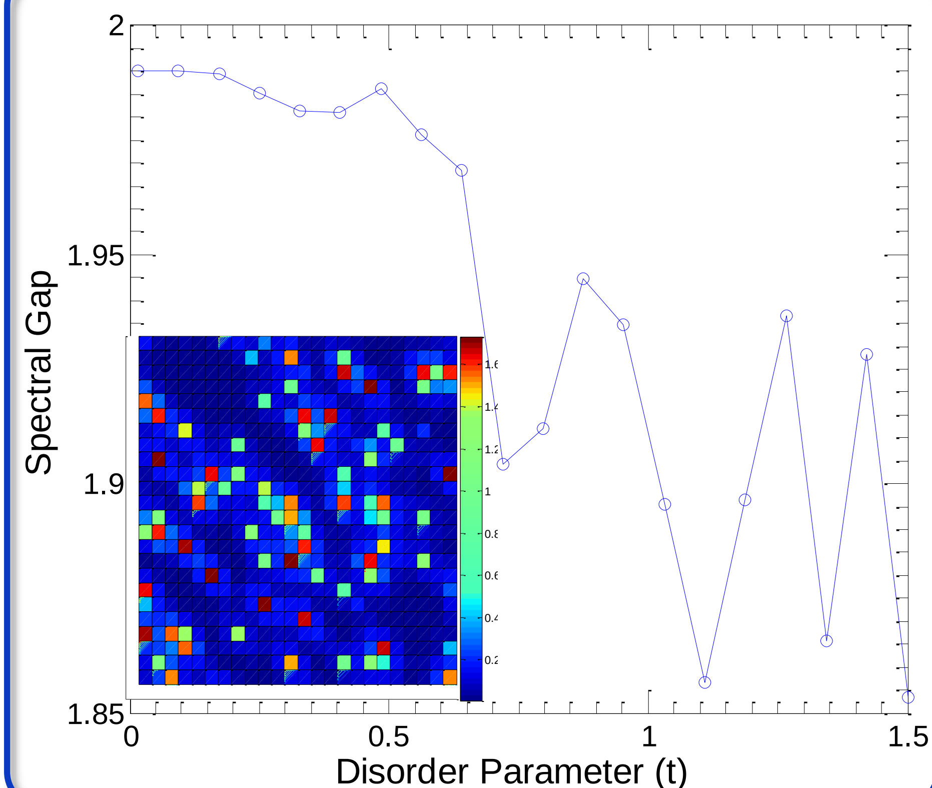
- Boron sites are occupied. Slight on-site disorder spreads occupation slightly.

Local Pairing Amplitude

- Local pairing amplitude maximal at boron sites.
- Sensitive to slight disorder, pairing amplitude less uniform than occupation.

On-site Disorder Only

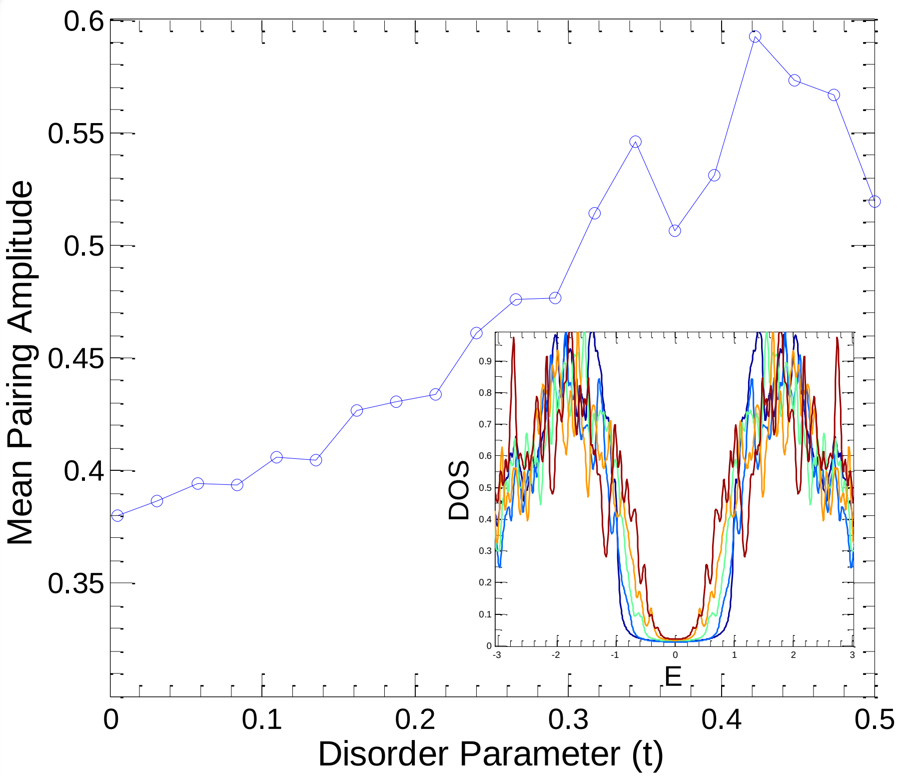


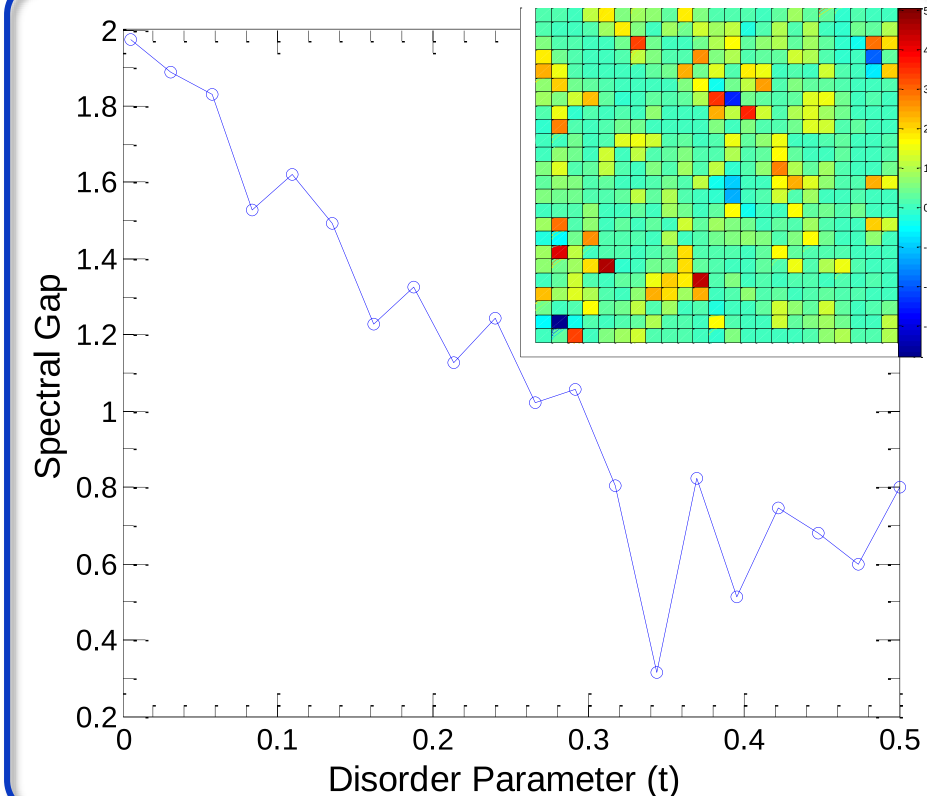


- Constant boron concentration, effect of **on-site** disorder only.
- MPA decreases with disorder, as expected.
- Spectral gap follows same behaviour as MPA.

- Spectral gap for different realizations of disorder.
- Decreases slightly with increasing disorder.
- **Gap remains finite** even at very high on-site disorder.

Structural Disorder Only

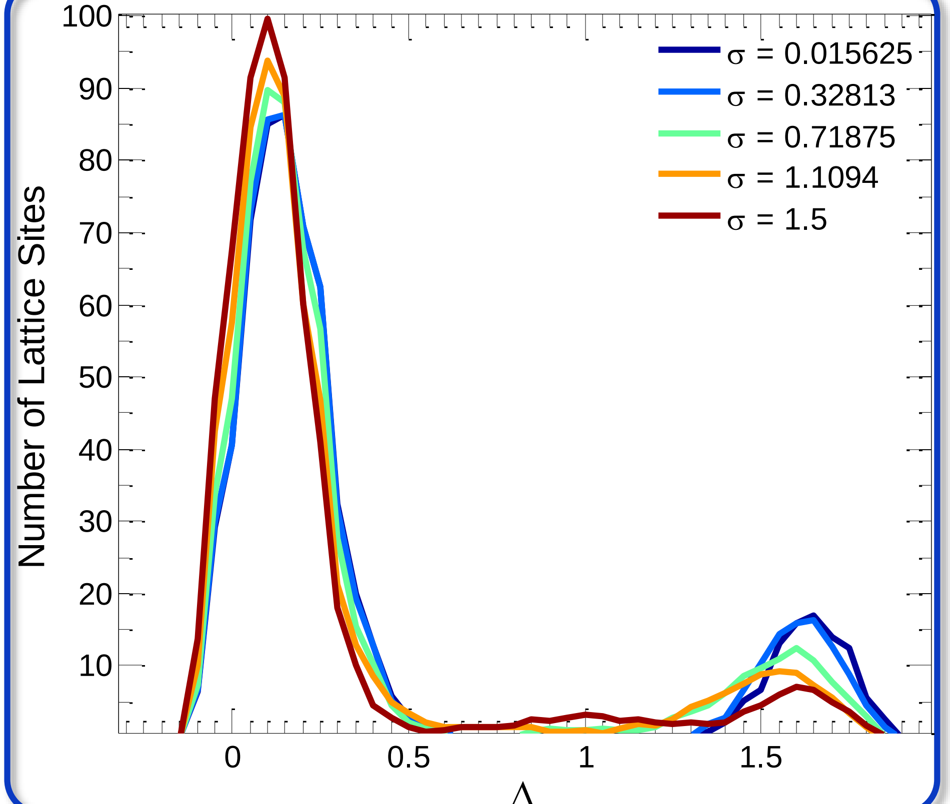


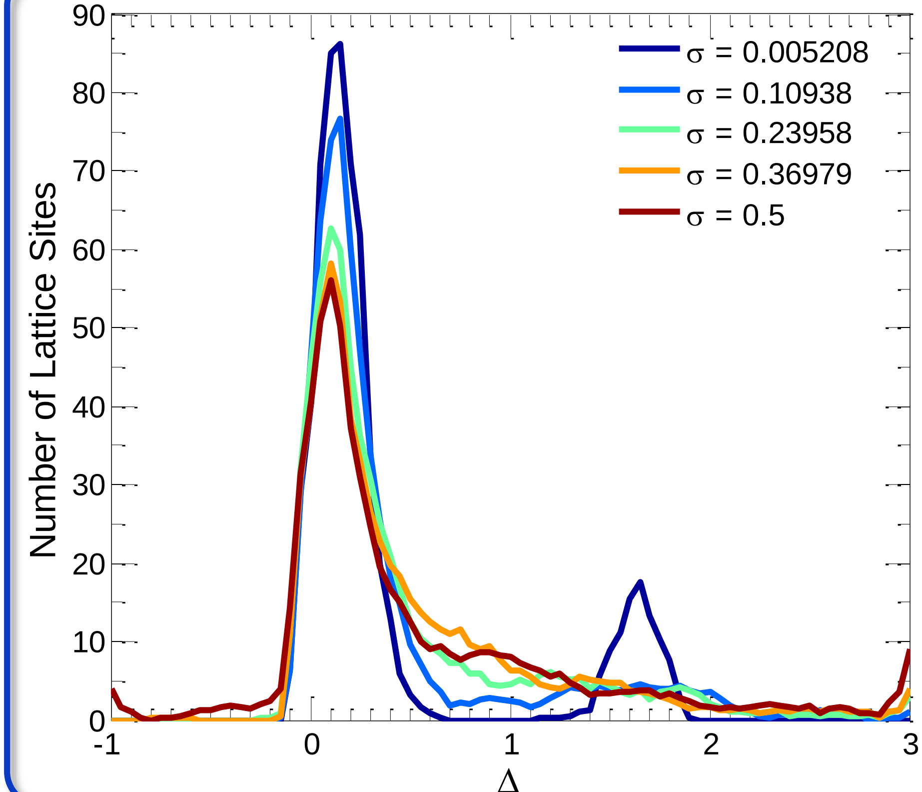


- Constant boron concentration, effect of **Structural** disorder only.
- MPA **increases** with disorder, unexpected.
- Spectral gap follows opposite behaviour to MPA.

- Spectral gap for different realizations of disorder.
- Decreases dramatically with increasing disorder.
- Gap remains finite, even at very high structural disorder.

On-site vs. Structural Disorder

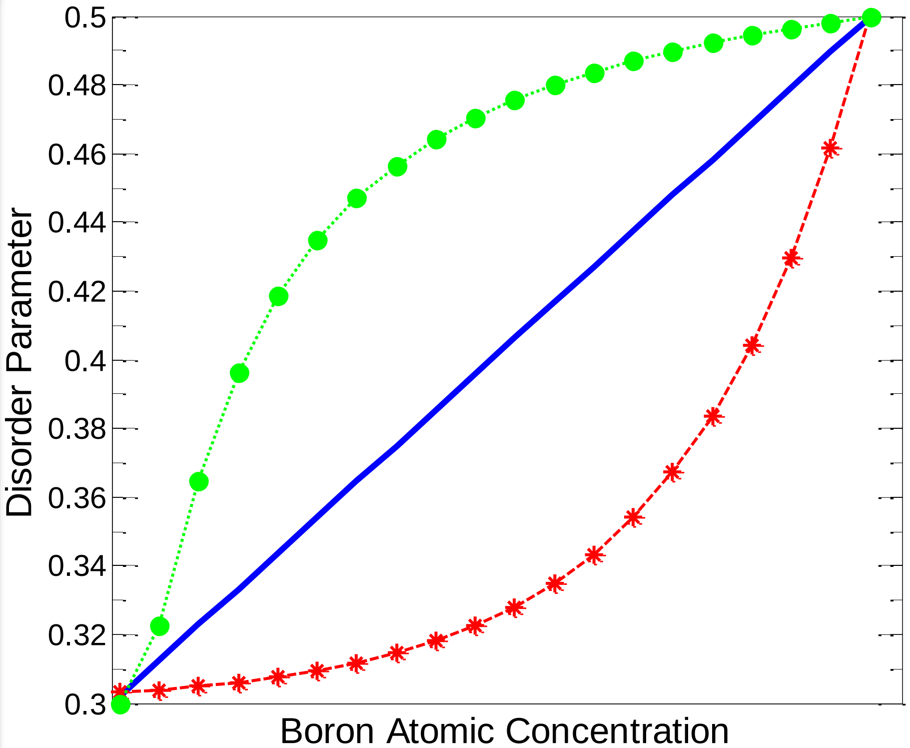


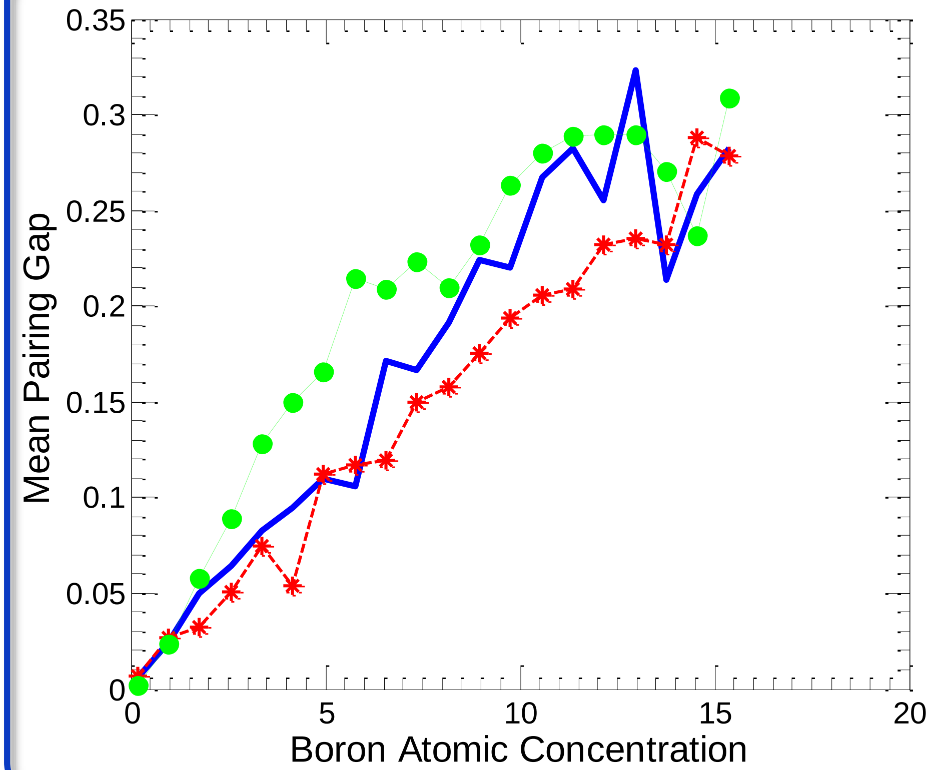


- Distribution of the local pairing amplitude (**on-site** disorder only).
- Distribution around 1.6 decreases sightly.
- Slight change in distribution around 0.
- Localized regions with relatively high pairing amplitude.

- **Structural** disorder. Distribution around 1.6 decreases rapidly.
- Pairing amplitude around 0 increases. Illustrates overall increase in the mean pairing amplitude.
- Interconnected regions with small PA.

Correlated Structural Disorder

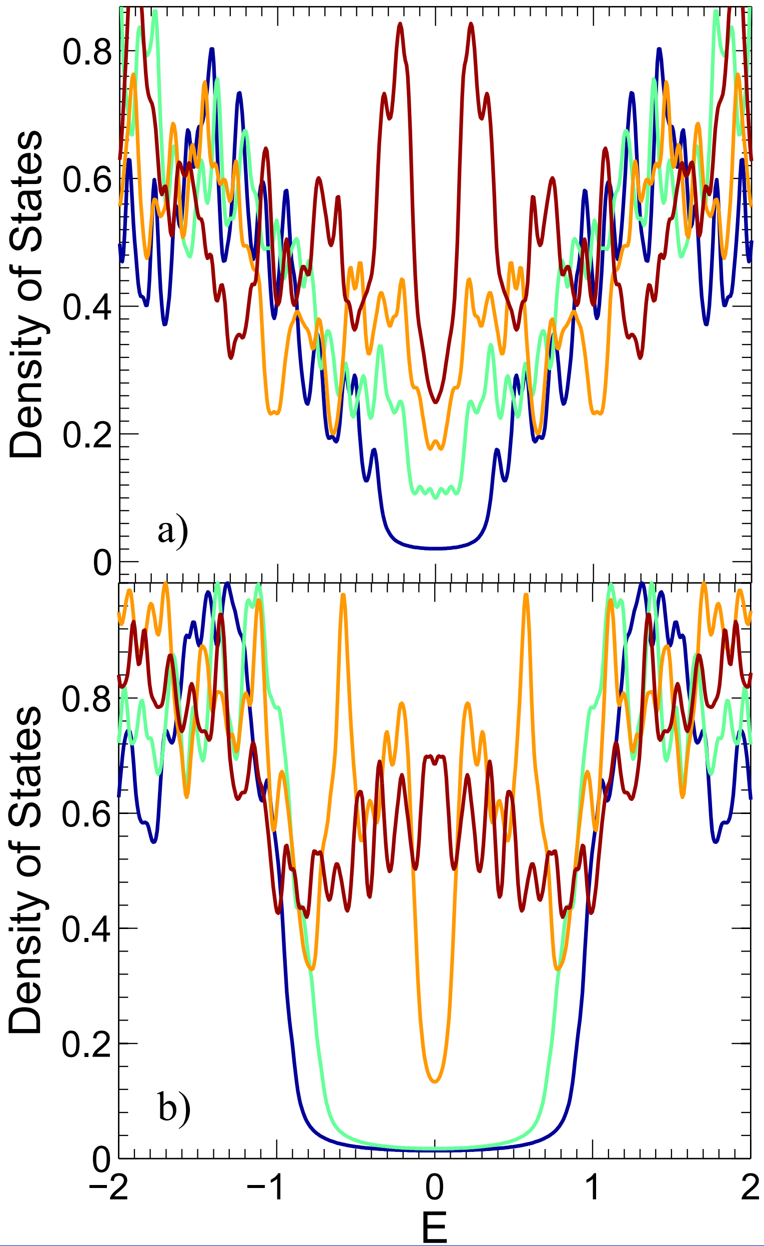


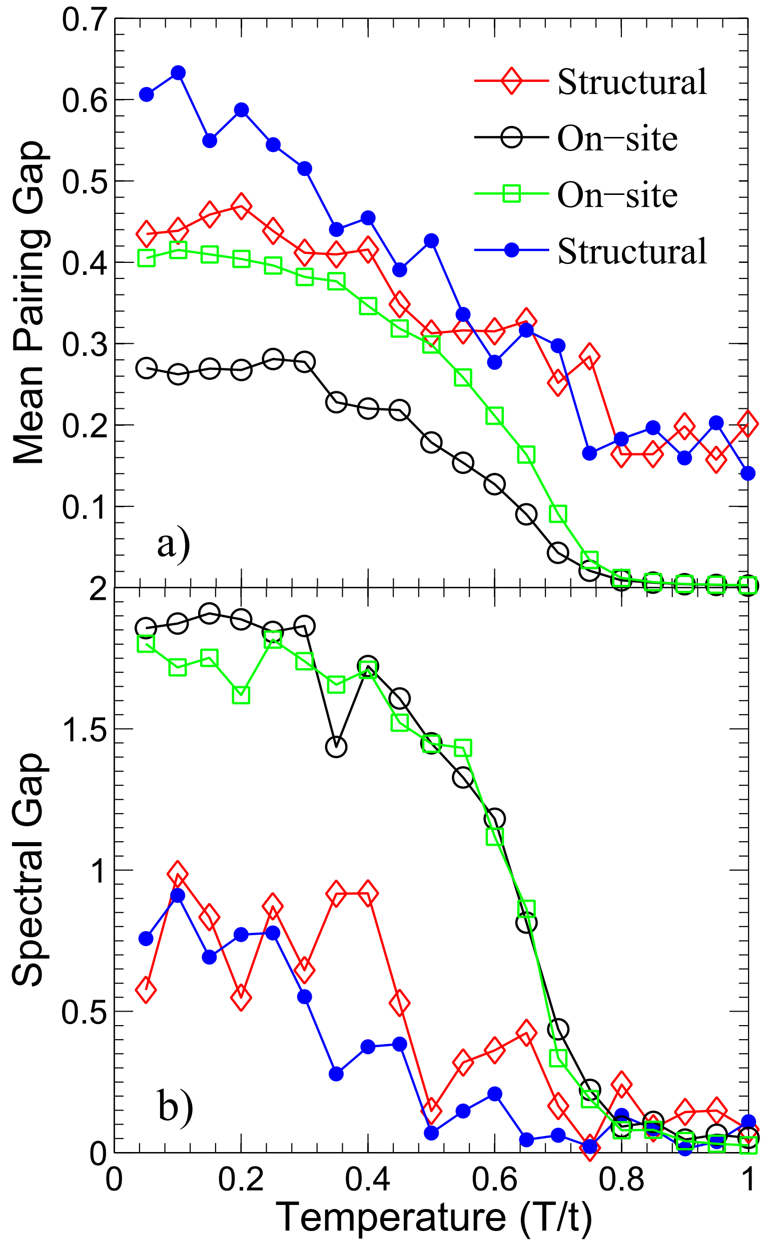


- Structural disorder level changes with boron doping.
- Studied different possibilities to compare with experiments.
- Here, assume some level of on-site disorder as well.

- Mean pairing amplitude as a function of the boron concentration.
- Saturation around 5% found in experiments.
- Suitable minimal Hamiltonian.

Temperature Dependence





Conclusion

- Possibility of type II superconductivity in BNCD demonstrated in samples with grain sizes 50 – 70 nm. Unusual features in high temperature MR.

- Suggest model of disordered array of weakly coupled Josephson junctions for samples closer to the Anderson-Mott transition. Possibility of BKT transition?

- Still to do: devices with different boron concentrations. AC Josephson effect. Thin film devices.

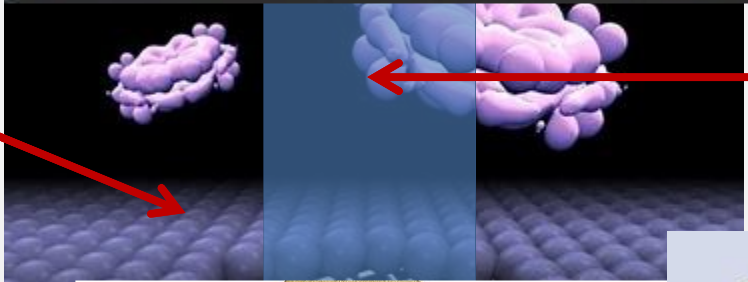
- Illustrated the interplay between structural and on-site disorder and the influence on the local and mean pairing amplitude.

- Shown that structural disorder can enhance mean pairing amplitude, results in more interconnected disordered superconductor with smaller local pairing amplitude.

- Still to do: build in Josephson junctions and vortices. Kubo treatment to merge theory and transport measurements.

Conclusion

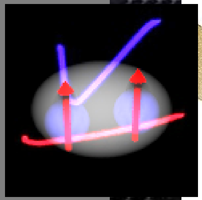
- Nano-scale nano-diamond devices
  - Quantum information
  - Bolometers, Medical imaging

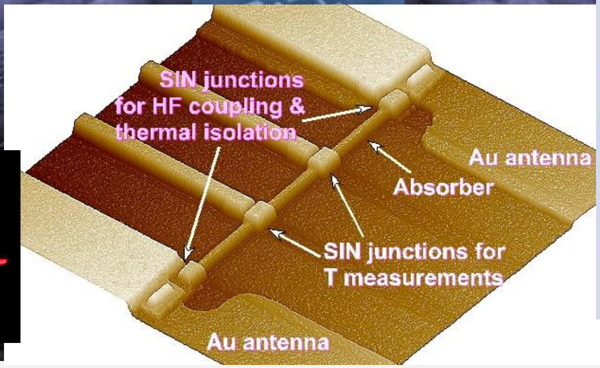


Electron beam

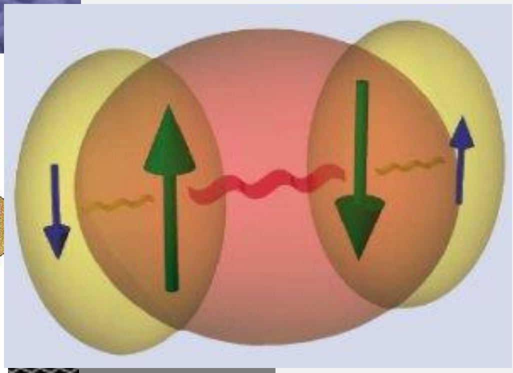
Nano-manipulated probes

Nano-manipulated probes





Leonid Kuzmin



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- Thank you for your attention!

Superconductivity BNCD

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