

# Spin-dependent Scattering Off Neutral Donors in Silicon Field Effect Transistors



C.C. Lo, J. Bokor

University of California, Berkeley  
Lawrence Berkeley National Laboratory



T. Schenkel

Lawrence Berkeley National Laboratory



J. He, A.M. Tyryshkin, S.A. Lyon

Princeton University

# Overview

## 1. Introduction

- Nuclear spin-state readout with donor qubits

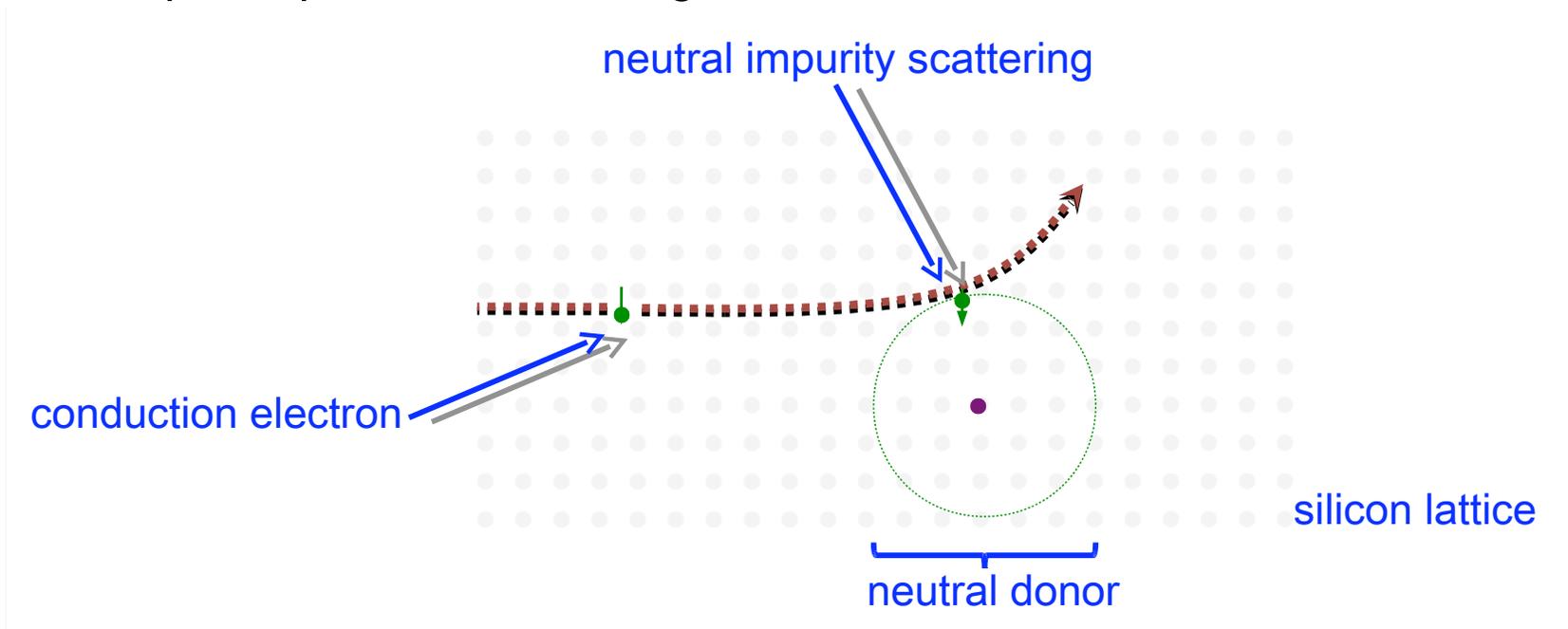
## 1. EDMR of spin-dependent scattering

- Electrically Detected Magnetic Resonance (EDMR)
- EDMR spectra
- EDMR of triple-gated devices

## 1. Summary

# Motivation

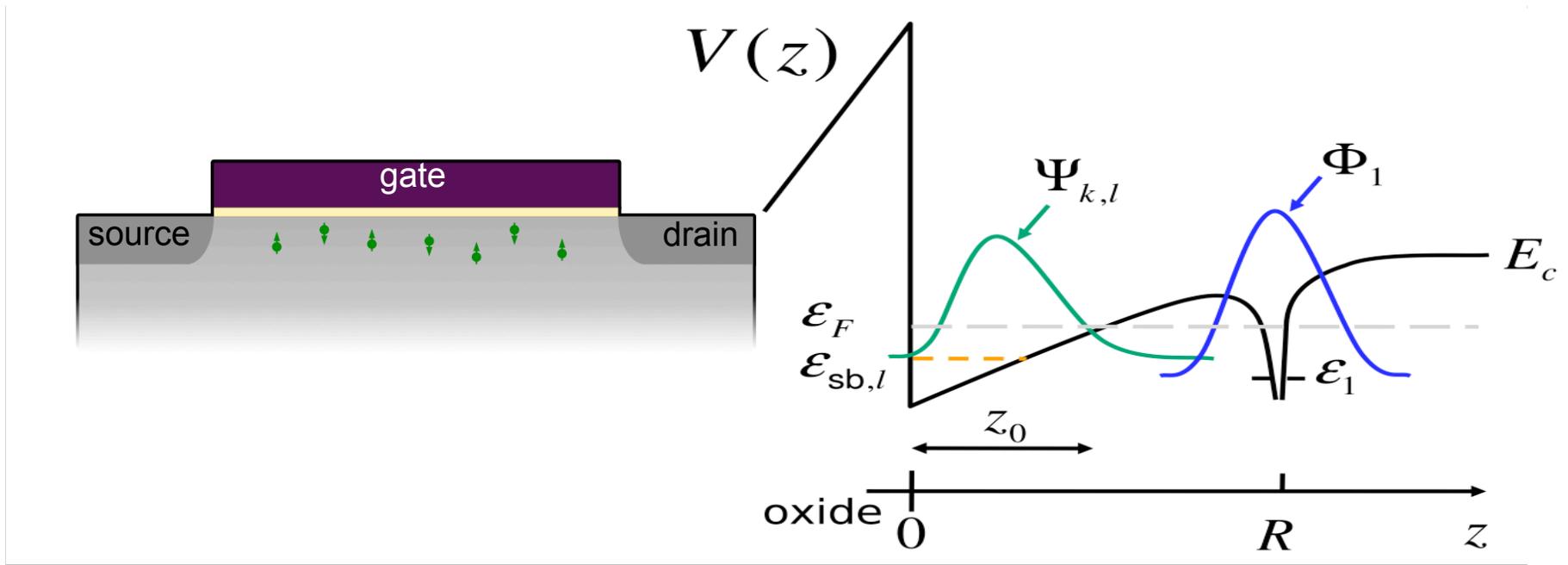
- Spin-state readout for donor qubits in silicon
  - Donor-quantum dot charge transfer
  - Donor- $P_b/D^-$  charge transfer
  - Spin-dependent scattering



- Non-equilibrium spin polarization detection in silicon

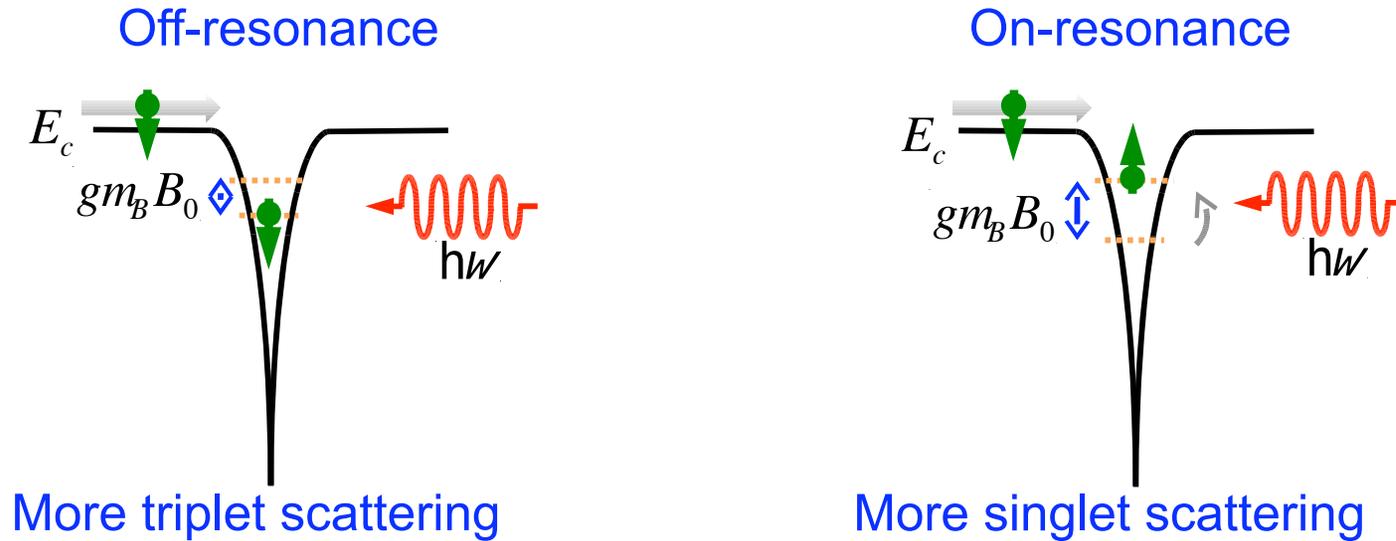
# Spin-dependent scattering with silicon 2DEG

- Accumulation-mode MOS Field Effect Transistors
  - Gate-tunable conduction electron (2DEG) density
  - Implanted neutral donors in channel



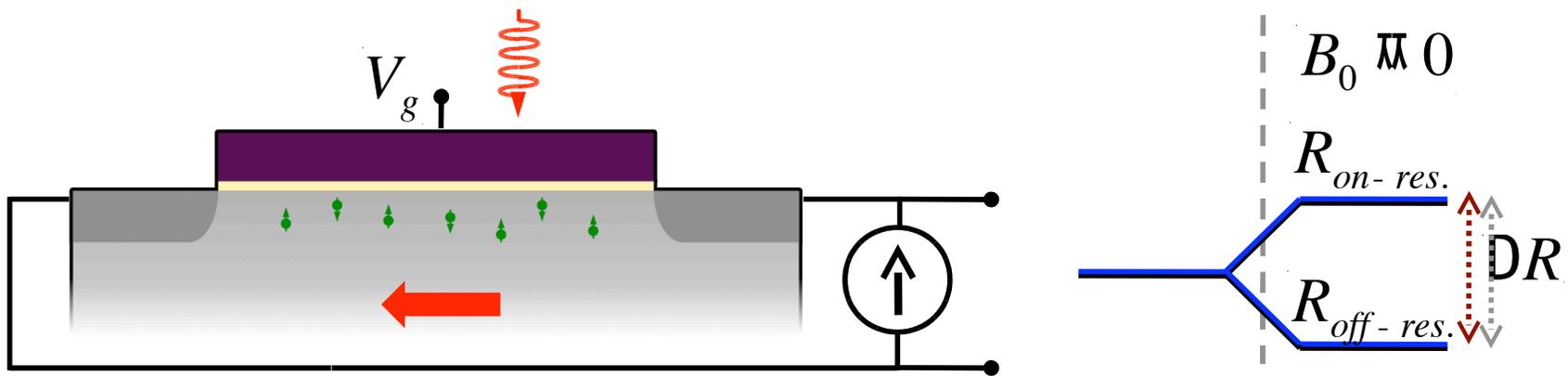
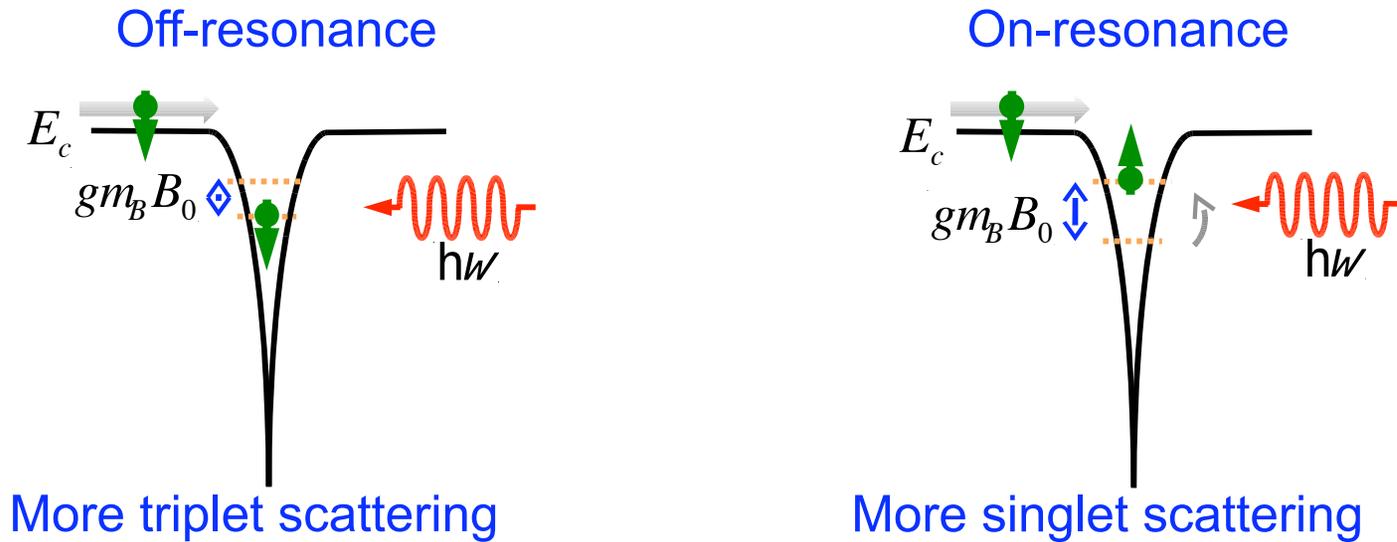
# Electrical detection of spin-dependent scattering

- Electrically Detected Magnetic Resonance:



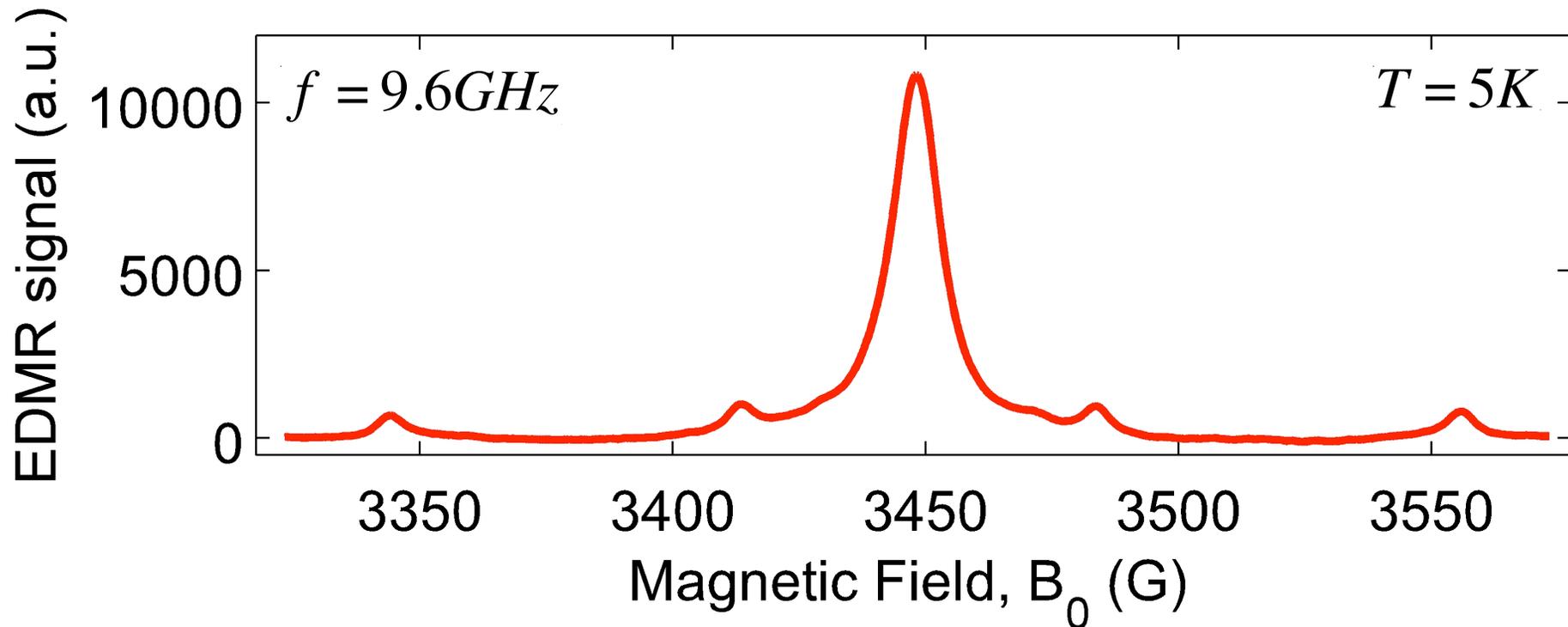
# Electrical detection of spin-dependent scattering

- Electrically Detected Magnetic Resonance:



# EDMR spectra of spin-dependent scattering

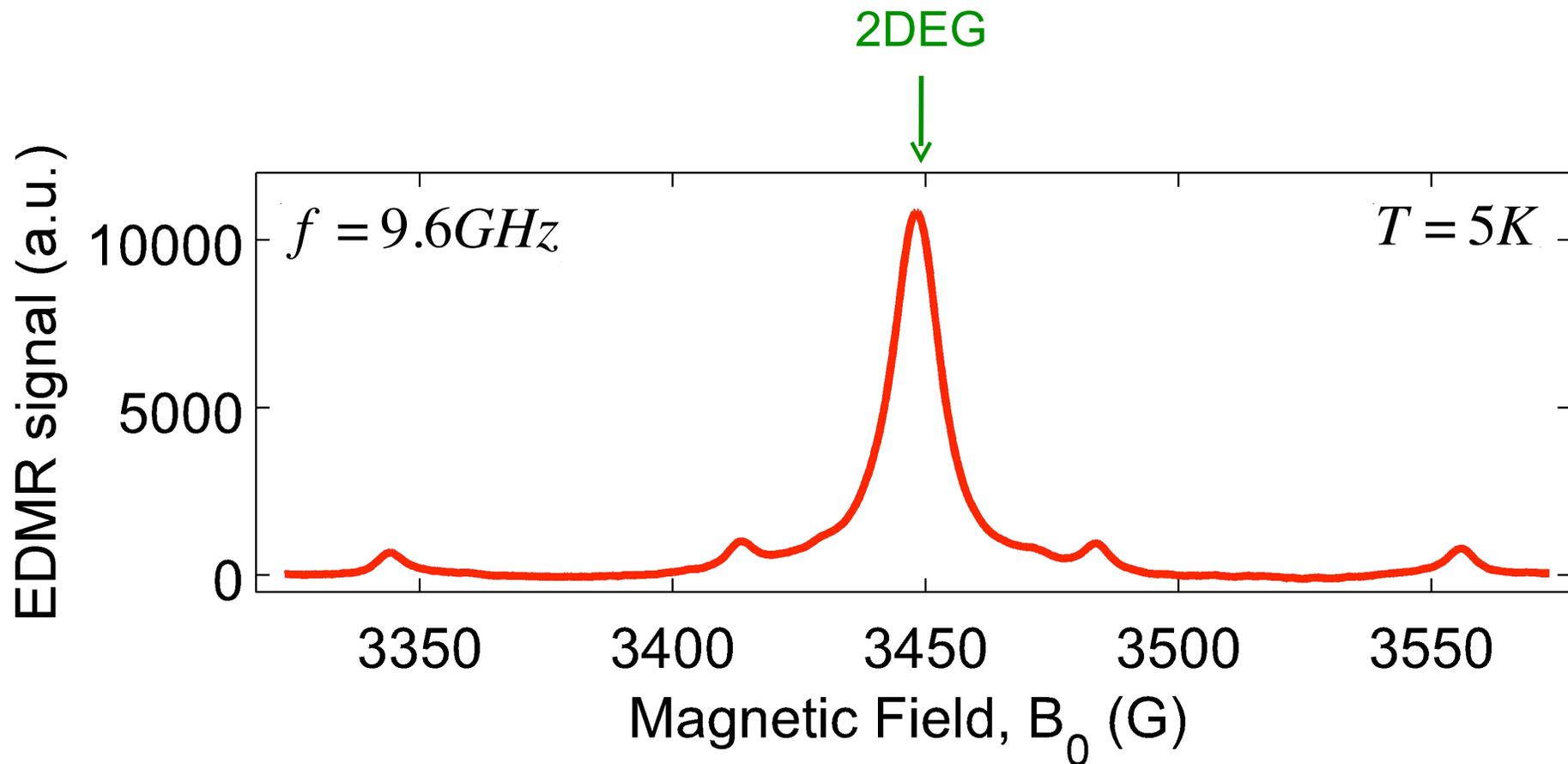
- EDMR signal is proportional to  $DR$



device size:  $L \times W = 160 \times 10 \mu m^2$

# EDMR spectra of spin-dependent scattering

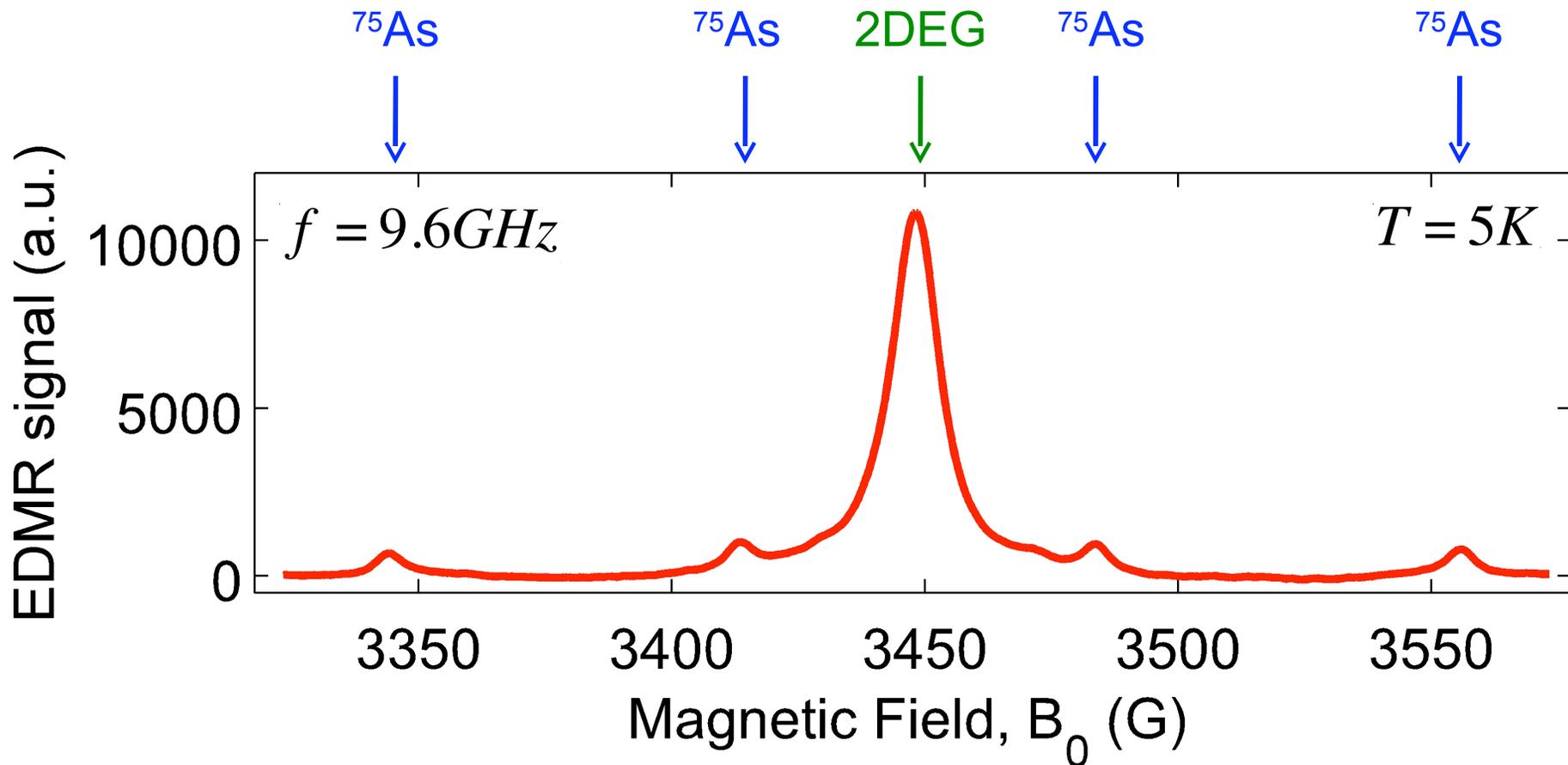
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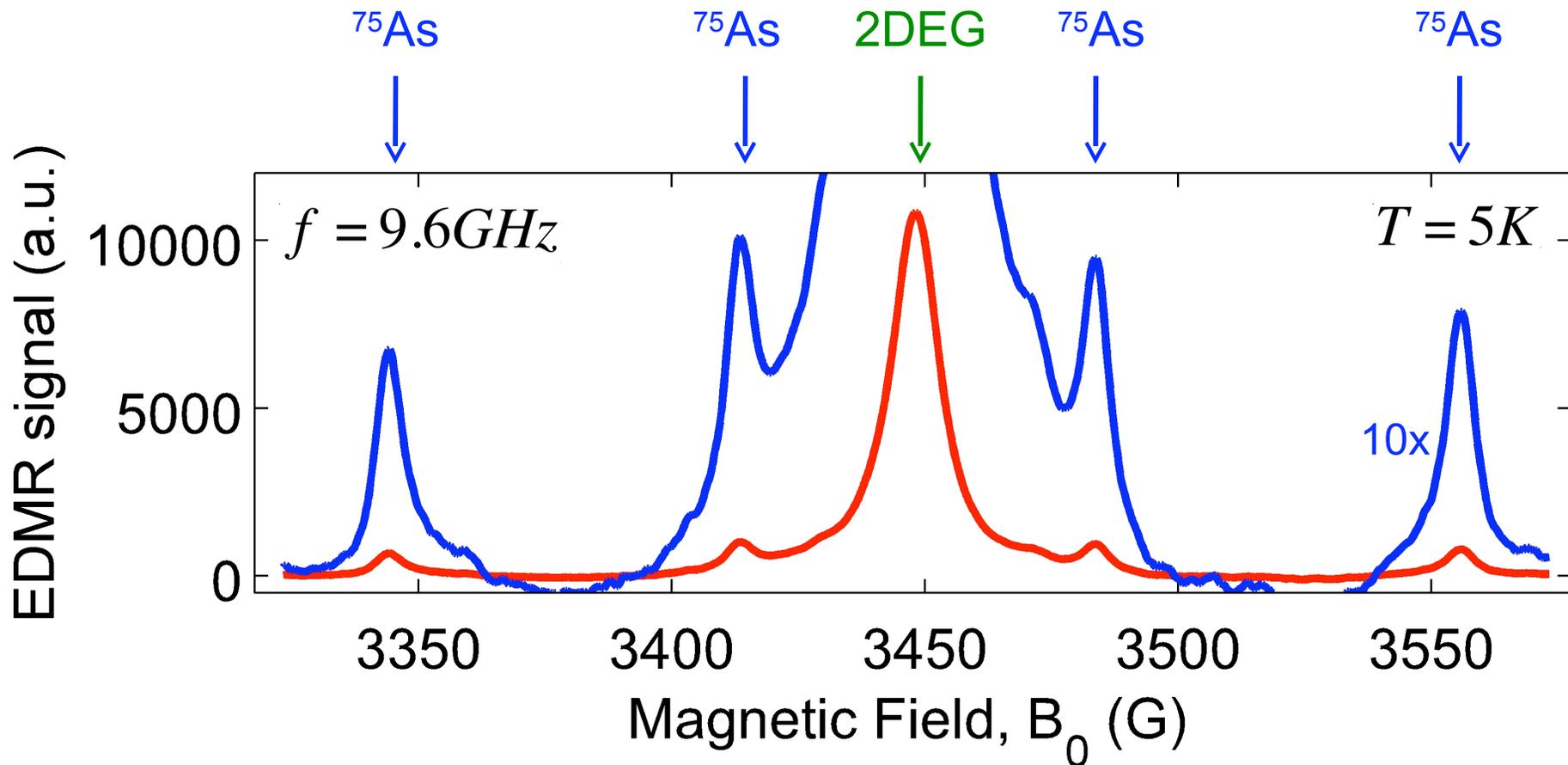
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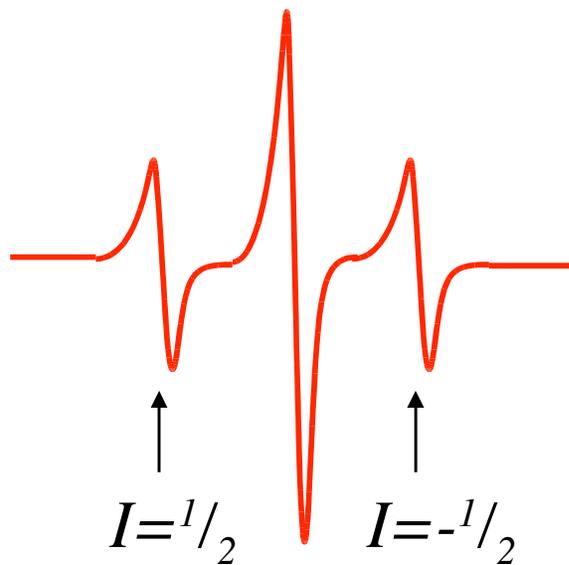


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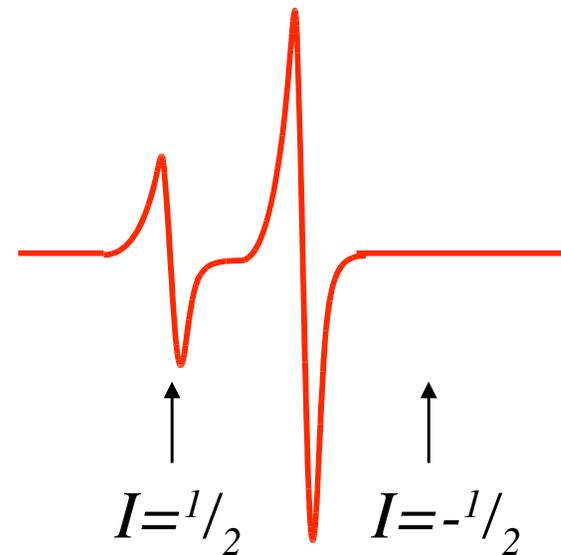
# Towards single nuclear spin readout

- Nuclear spin-state readout by spin-dependent scattering:

Large ensemble of donors

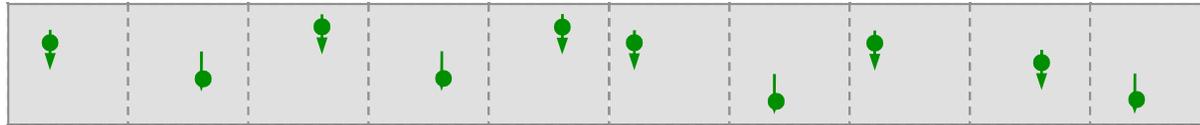


Single/few donors

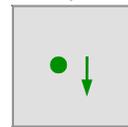


# Constant scaling for spin-dependent scattering?

Large device:



Small device:



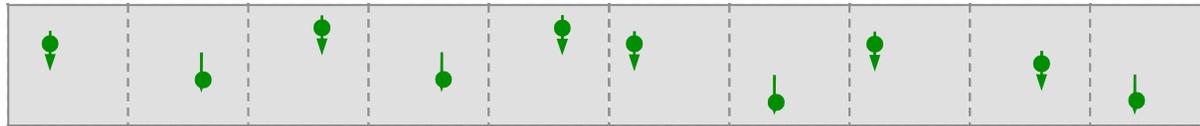
Constant donor density



$$\frac{DR}{R} = \text{constant}$$

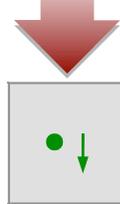
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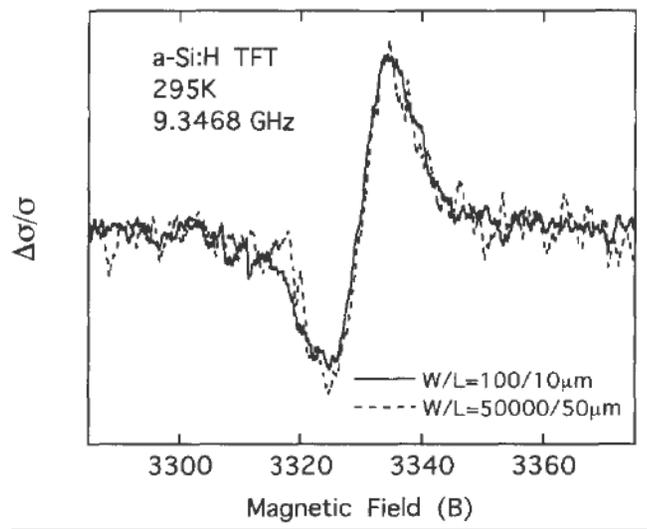


Small device:

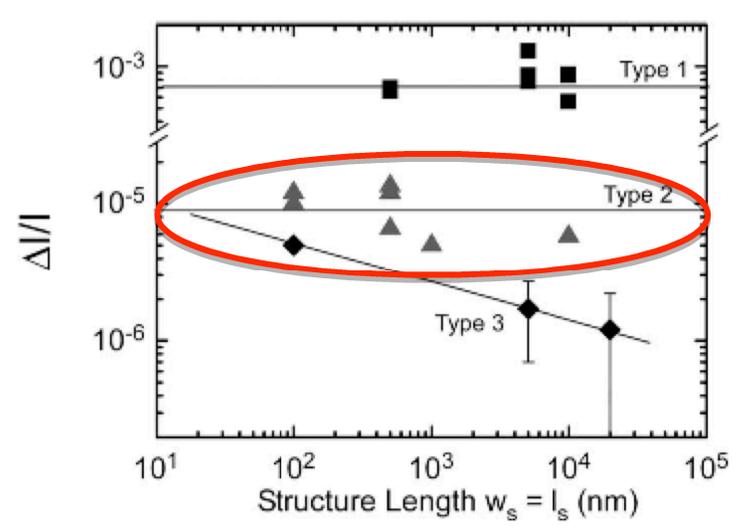
Constant donor density



$$\frac{DR}{R} = \text{constant}$$



Graeff et al., J. of Non-Crystalline Solids (1996)



McCamey, et al., APL (2006)

# EDMR signal and carrier polarization

- EDMR donor amplitude depends on 2DEG spin polarization:

$$DR \propto \langle p_c p_d \rangle \propto \langle p_c^2 \rangle$$

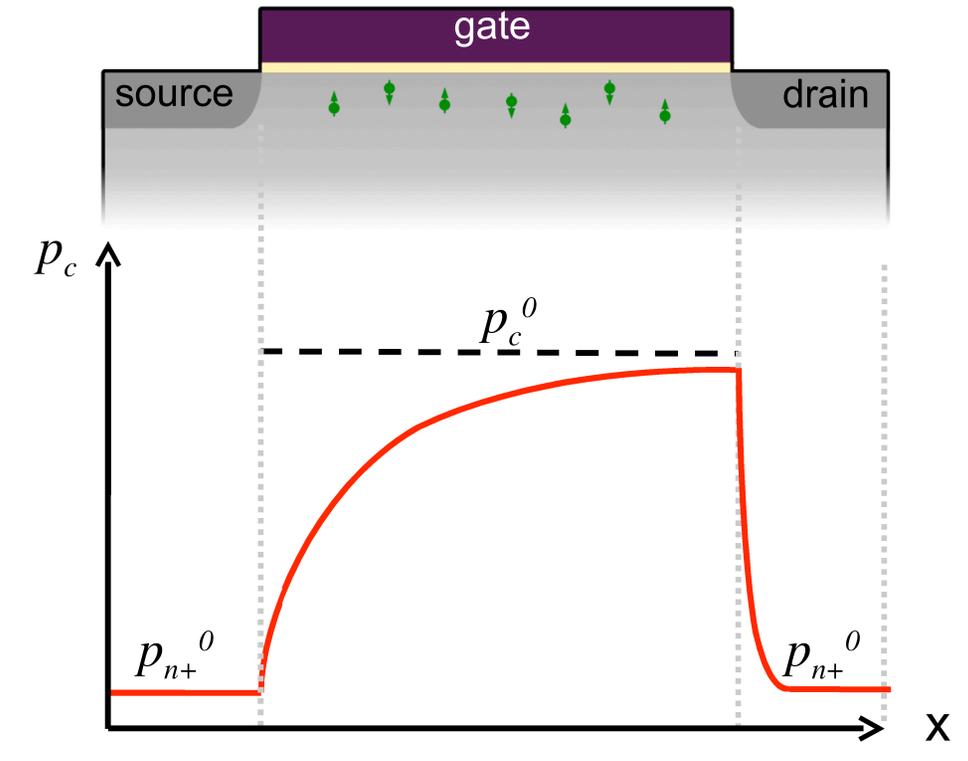
$$p_c = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}}$$

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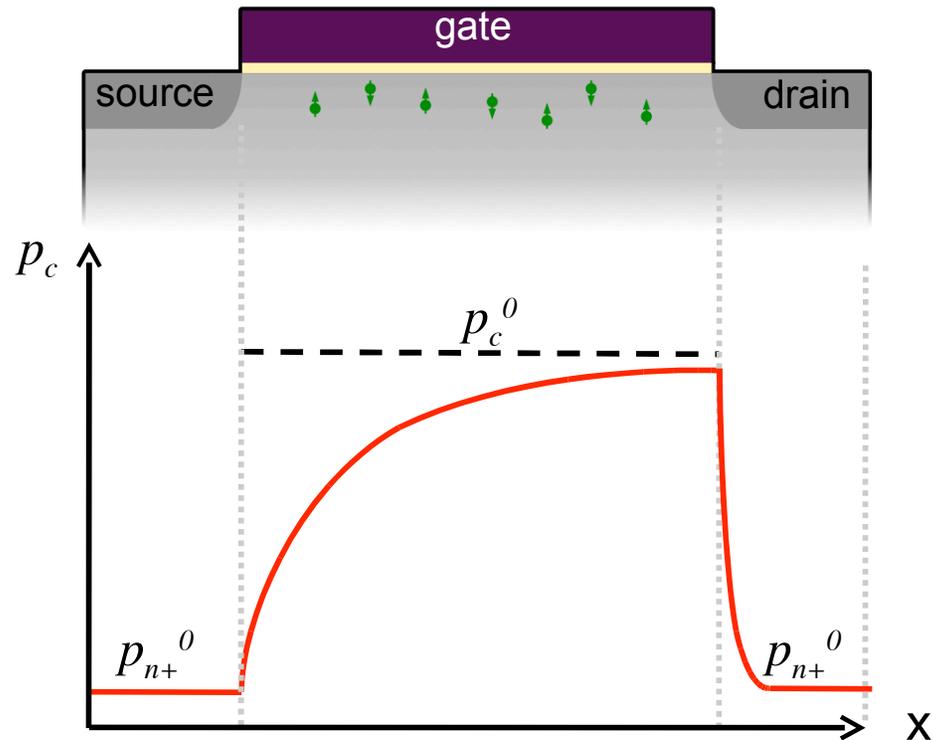


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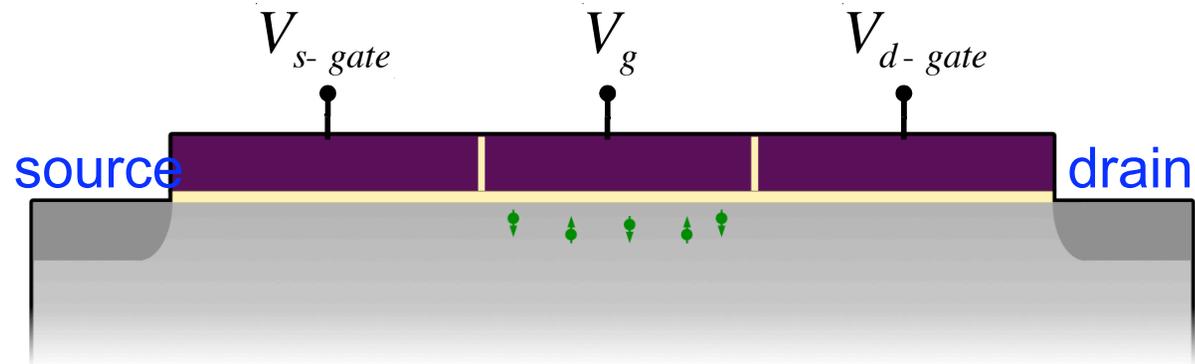
$$p_c = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}}$$



- Locally implanted donors can be used to probe local spin polarization.

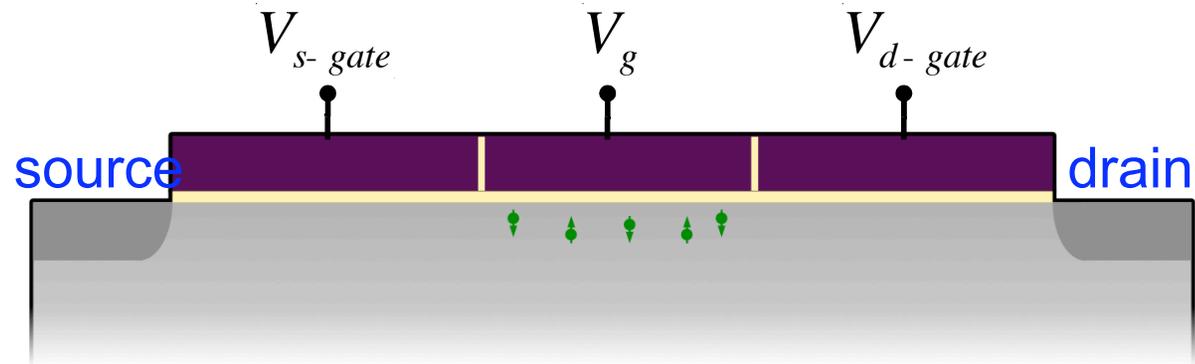
# Gate-tunable spin injection

- Triple-gate structure to enhance EDMR signal:



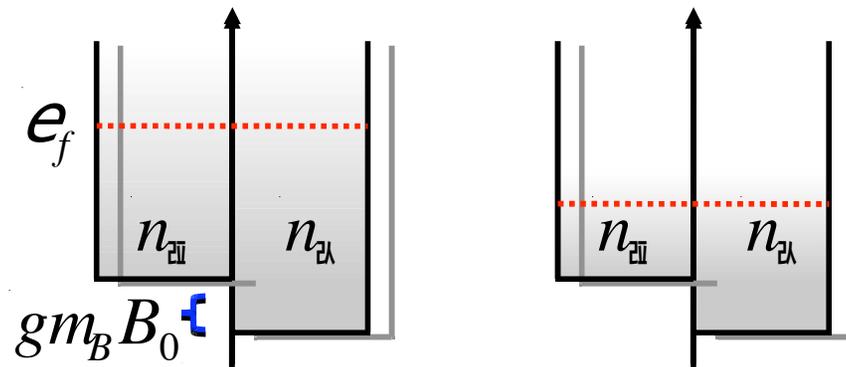
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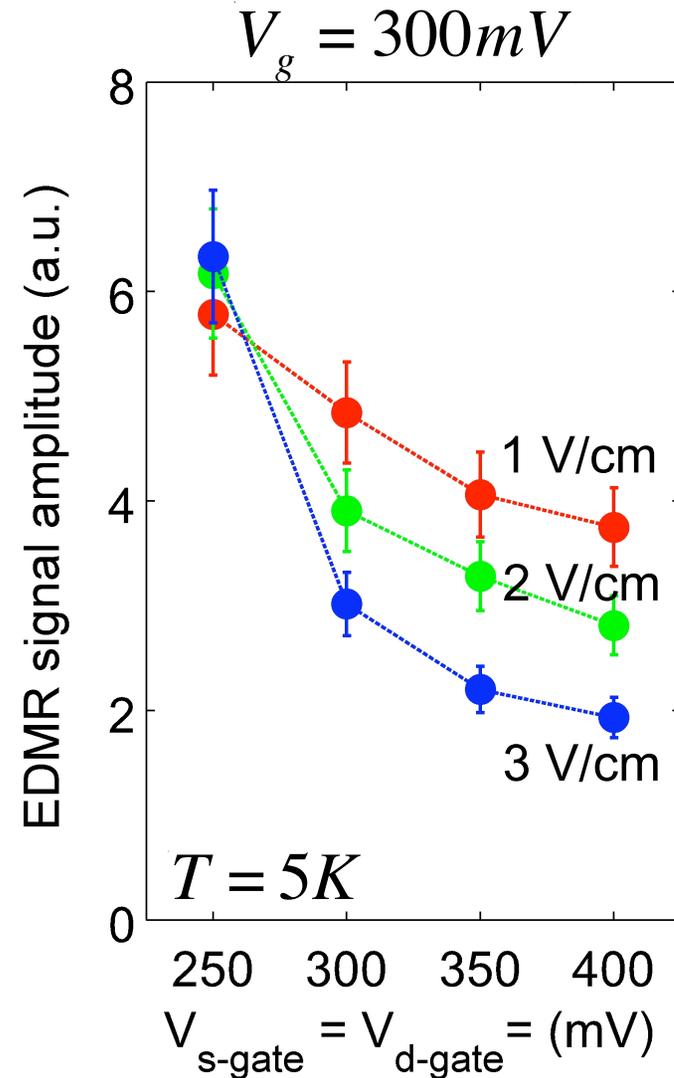
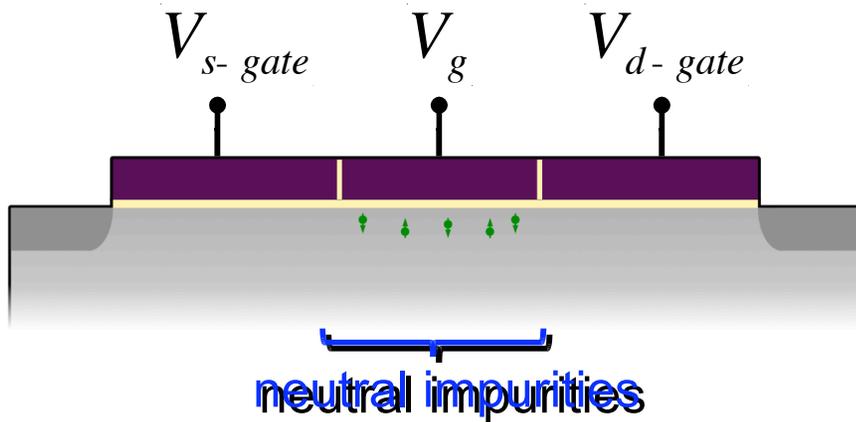


- Gate-tunable thermal equilibrium spin polarization:

$$p_c = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}} = \frac{gm_B B_0}{2(e_f - e_0)}$$

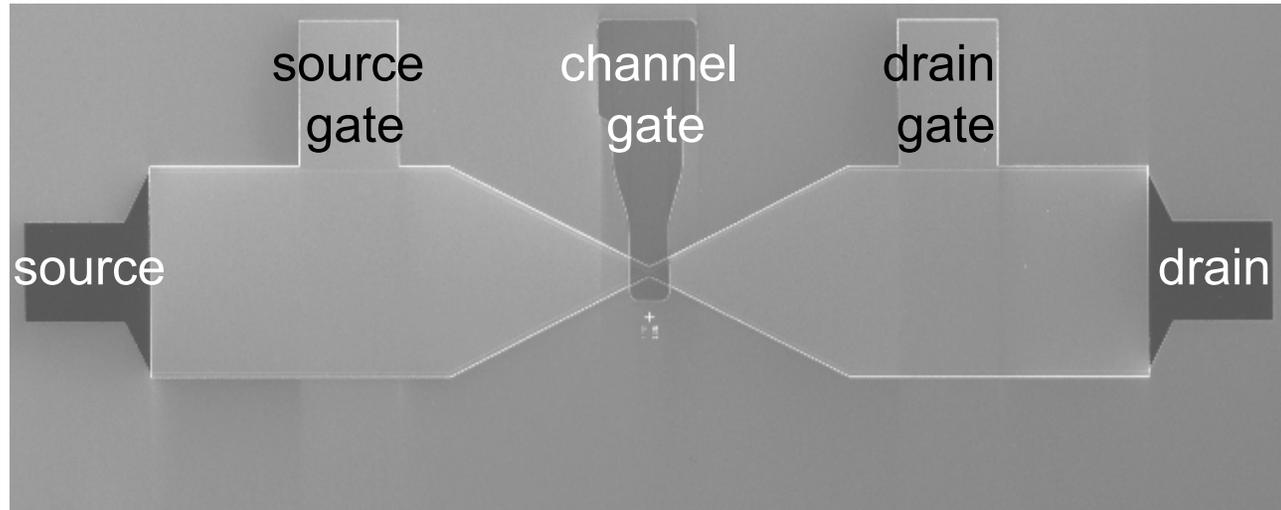


# Spin-dependent scattering signal enhancement

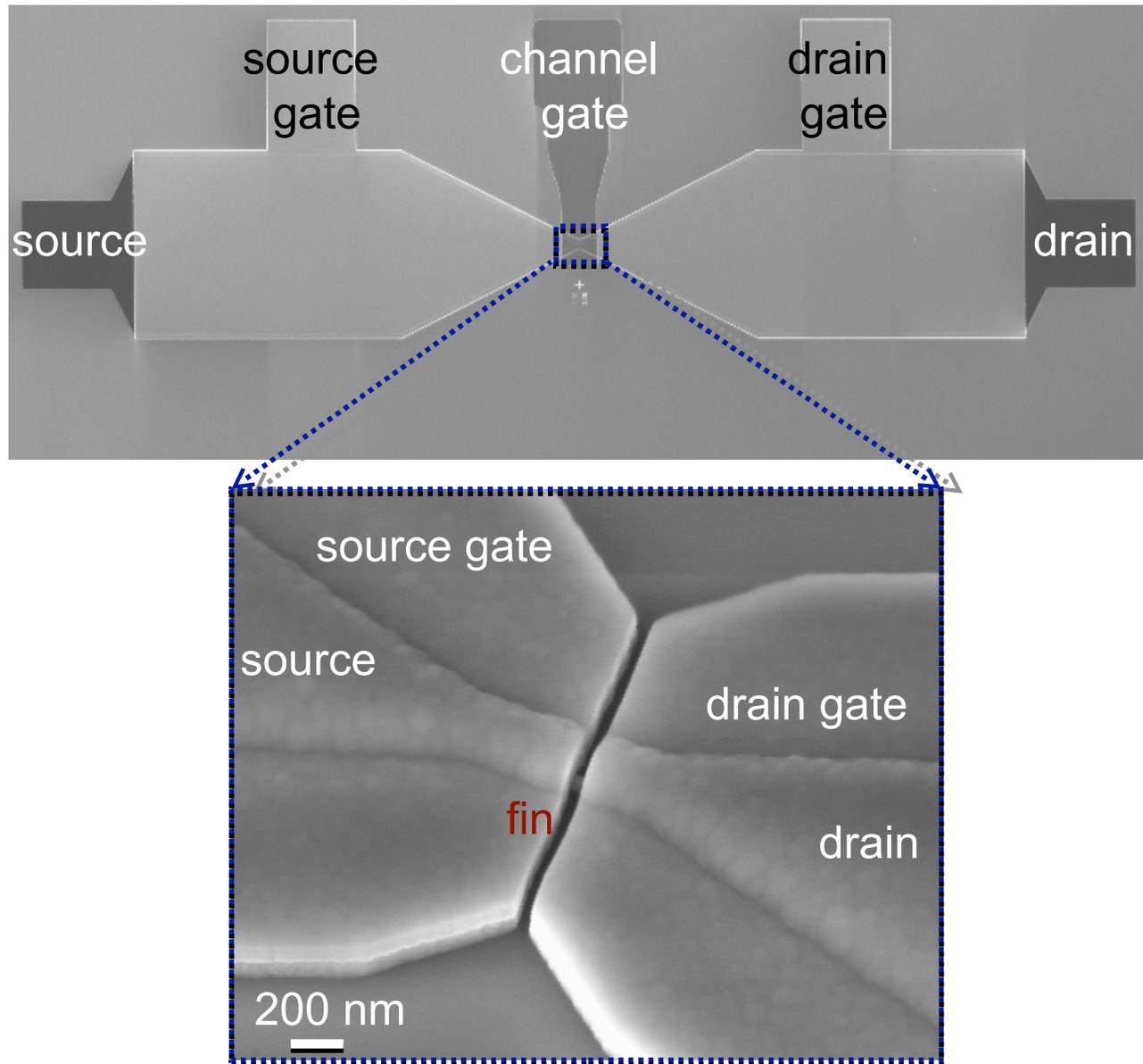


device size:  $L \times W = 40 \times 40 \mu\text{m}^2$ ,  $L_{s\text{-gate}} = L_{d\text{-gate}} = 60 \mu\text{m}$

# Towards few donor devices



# Towards few donor devices



# Summary

- Spin-dependent scattering signal decreases with device size due to low polarization of injected carriers.
- Triple-gate devices show enhanced spin-dependent scattering signal amplitudes with gate-tunable spin polarization.
- Injected carrier polarization can be probed by monitoring the spin-dependent neutral impurity scattering signal in an EDMR measurement.

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