The 11th School of Mesoscopic Physics: Quantum Control and Sensing

Quantum Sensing and Imaging Using Diamond NV Center

Donghun Lee

Department of Physics, Korea University

Beginning the era of quantum technology

Quantum Mechanics

- Duality
- Uncertainty
- Superposition
- Entanglement

반도체 이론, 기초 실험

Se photocell (1931, Weston)

진공튜브 컴퓨터 (1946, ENIAC)

Quantum Technology

- Quantum computation
- Quantum communication
- Quantum simulation
- Quantum sensing

양자정보 이론, 기초 실험

양 자 센 서 (?)

양자컴퓨터 (?)

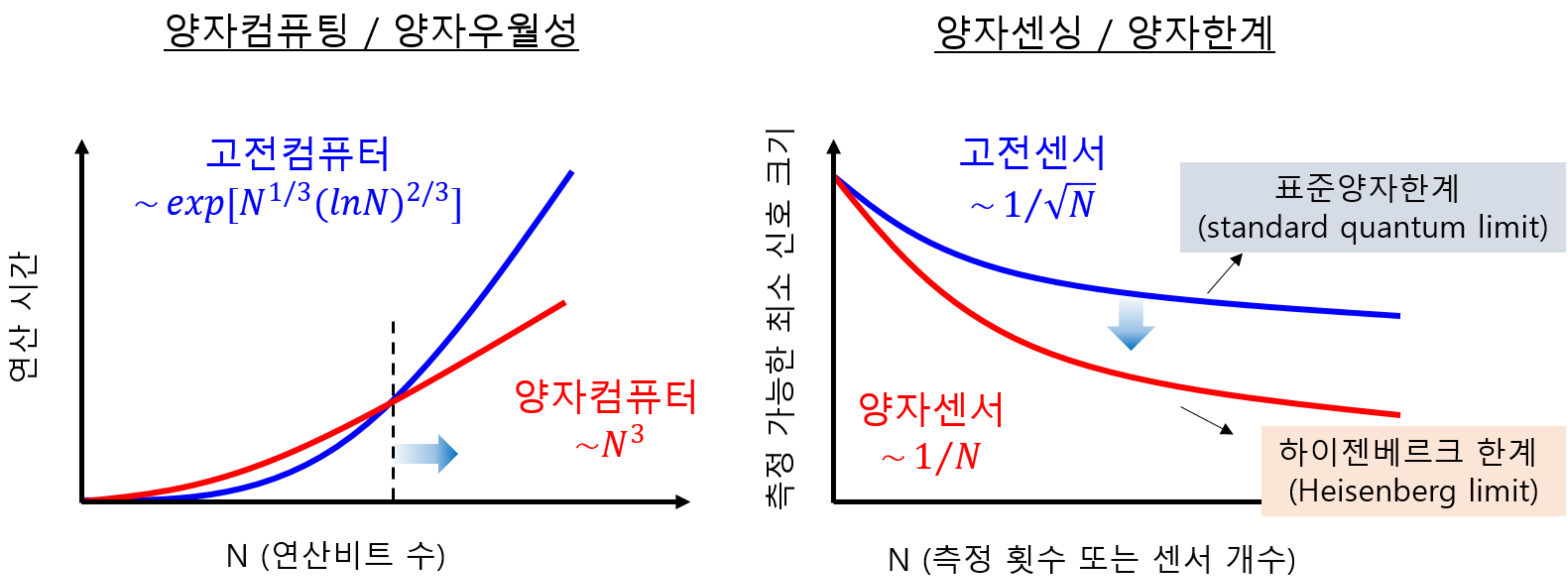
Quantum sensing ?

개념 및 정의	참고문헌
양자시스템(예, 큐비트) 또는 양자결맞음(예, 중첩)을 이용하여 물리량(예, 온도, 자기장)을 측정하는 기술	[1]
양자얽힘(entanglement), 압착(squeezing) 등 양자특성을 이용하여 물리량을 양자한계(standard quantum limit) 이하로 측정하는 기술	[1]
고전시스템만을 사용했을 때 얻을 수 있는 것보다 더 나은 민감도와 분해능을 얻기 위해 양자얽힘과 같은 양자특성을 활용하는 기술	[2]
기존 센서/이미징의 정밀도를 획기적으로 개선하고 새로운 초정밀 양자센서/이미징 산업을 창출할 수 있는 기술을 포함	[2]

[1] C. L. Degen, F. Reinhard, P. Cappellaro, "Quantum Sensing", Reviews of Modern Physics 89, 0034-6861, 2017.

[2] 정보통신기술진흥센터 ICT R&D 기술로드맵 2023.

Quantum sensing and quantum limit



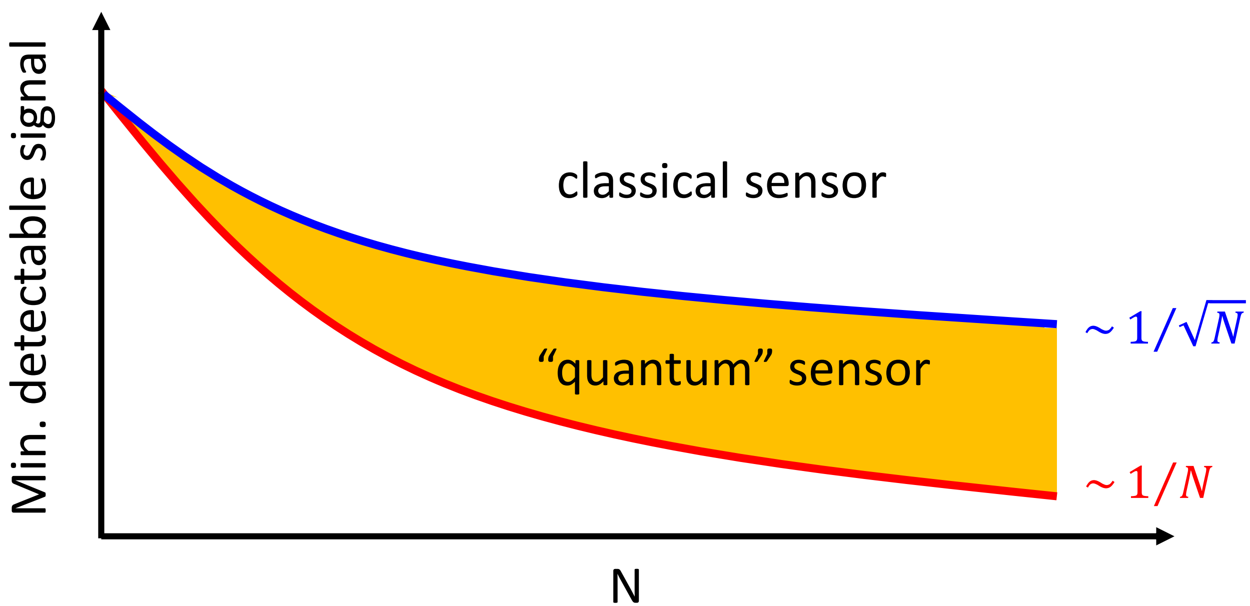
L. Pezze et al., Rev. Mod. Phys. 90, 035005 (2018)

Sensitivity of quantum sensor

민감도 (sensitivity) $\approx \dfrac{1}{\sqrt{N}} \dfrac{1}{\sqrt{T}}$ $\left[\dfrac{물리량}{\sqrt{Hz}}\right]$

N : # of measurements or # of sensors

T : Coherence time , $T_1, T_2, T_2{}^*$

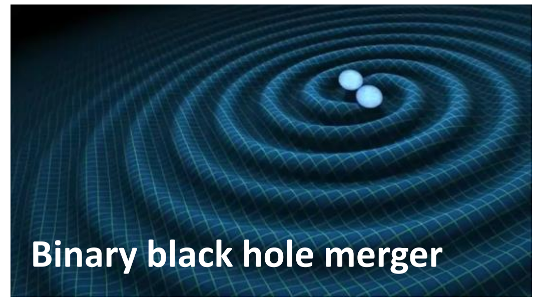


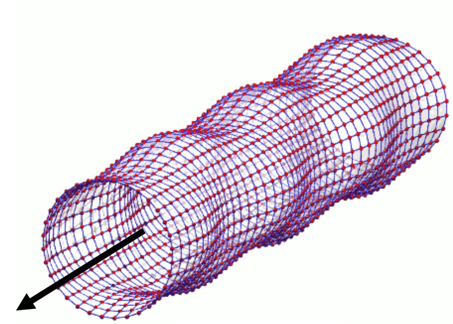
표준양자한계
(standard quantum limit)

하이젠베르크 한계
(Heisenberg limit)

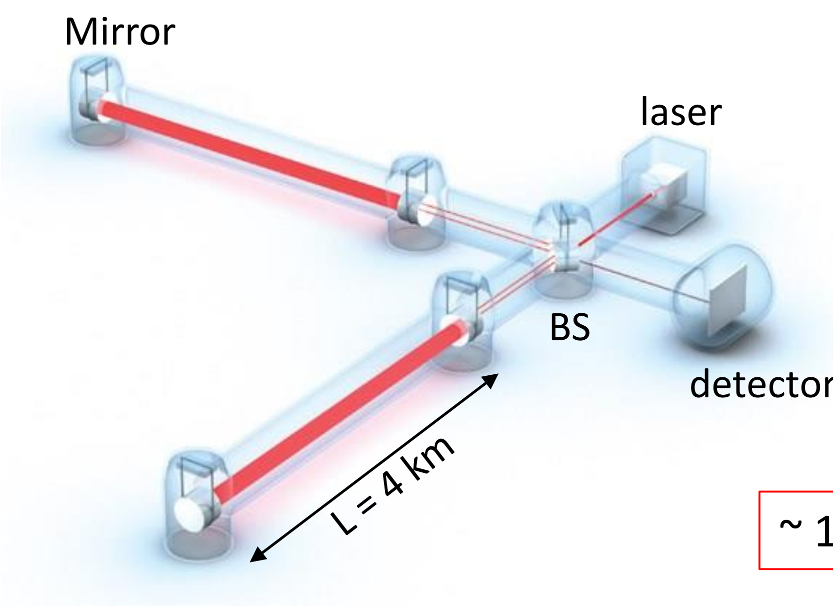
Example : Gravitational Wave Detection

LIGO (**L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory), Nobel prize at 2017

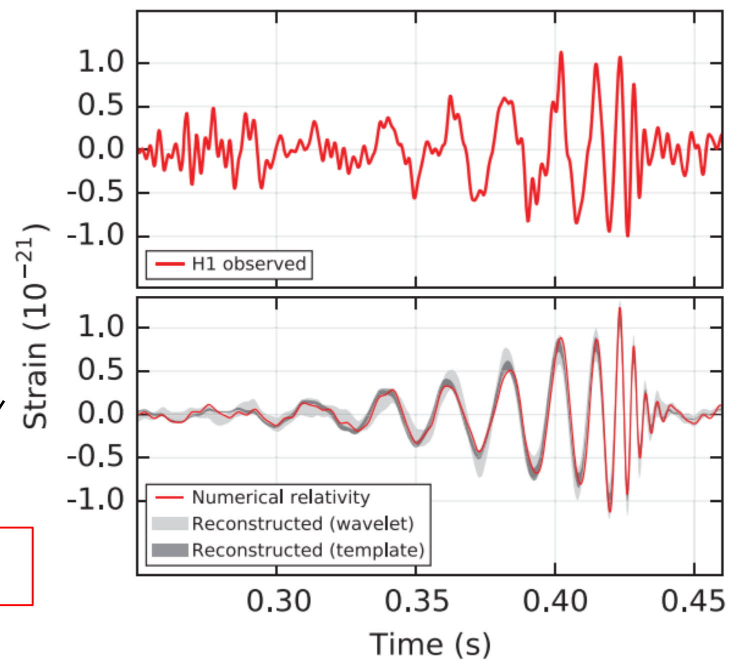




gravitational wave



~ 10^{-18} m

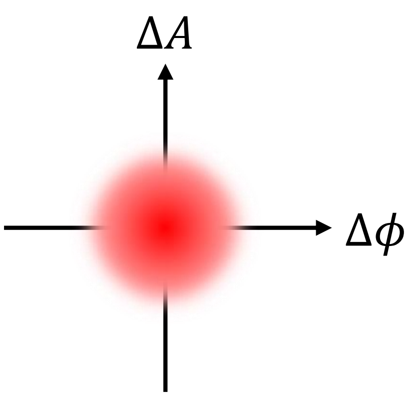


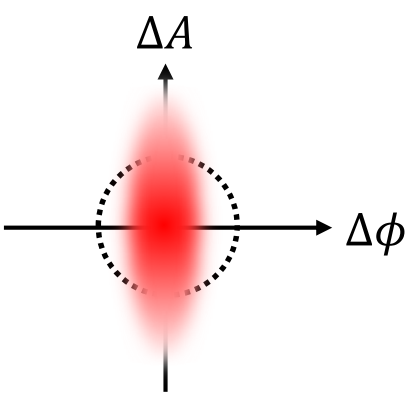
B.P. Abbott *et al.*, PRL (2016)

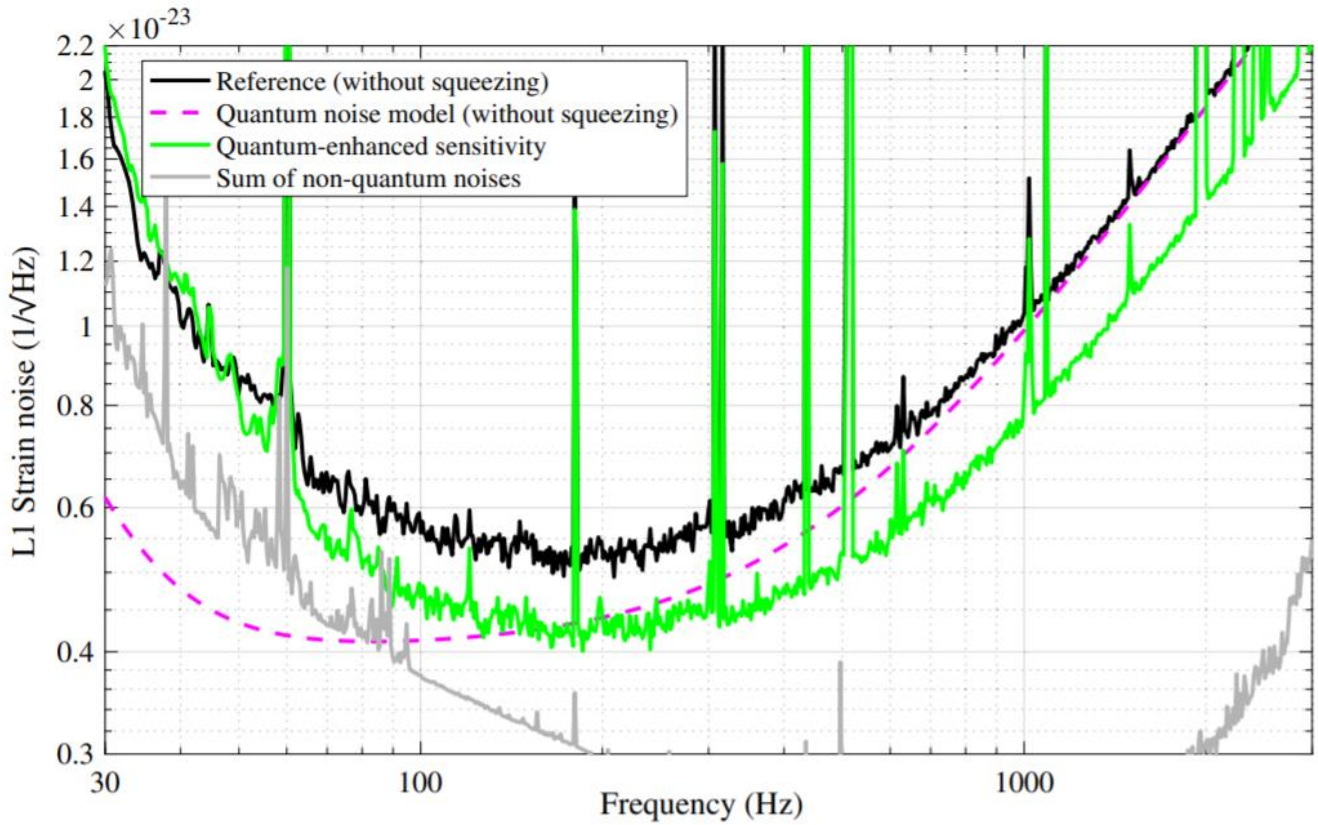
Example : Gravitational Wave Detection

LIGO (**L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory), Nobel prize at 2017

50 % improvement with quantum squeezed light





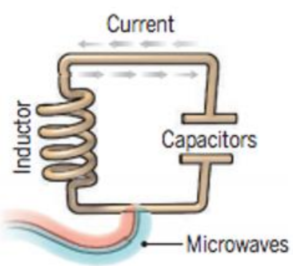


M. Tse *et al.*, PRL 123, 231107 (2019)

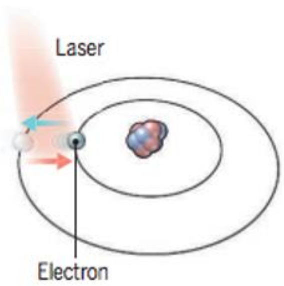
Classification of quantum sensing

➢ 양자센서에 따른 분류

초전도 소자

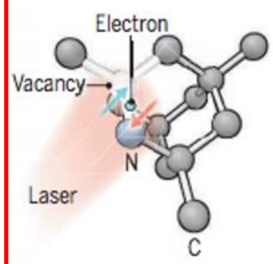


이온, 원자

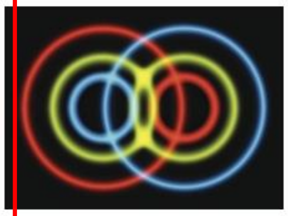


반도체 양자점

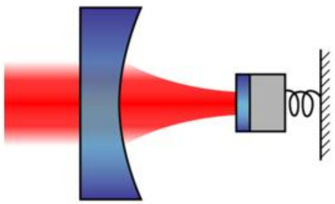
NV 센터



광자



역학계

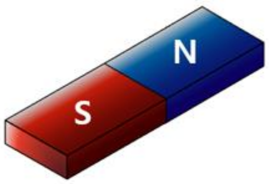


➢ 센싱 물리량에 따른 분류

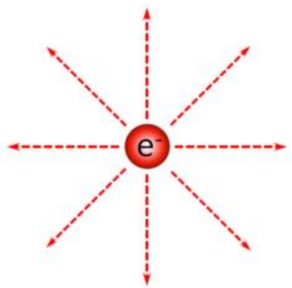
중력/힘

회전/각속도

자기장/스핀



전기장/전하



온도

시간

Classification of quantum sensing

대분류	소분류	큐빗	측정하는 양	진동수	초기화	상태 읽기
중성 원자	원자 증기	원자 스핀	**자기장, 회전, 시간/진동수**	dc–GHz	광학	광학
	차가운 구름	원자 스핀	**자기장, 가속도, 시간/진동수**	dc–GHz	광학	광학
갇힌 이온	–	수명이 긴 전자 상태	**시간/진동수**	THz	광학	광학
			회전	–	광학	광학
		진동 모드	**전기장, 힘**	MHz	광학	광학
리드버그 원자	–	리드버그 상태	**전기장**	dc, GHz	광학	광학
고체 스핀 (앙상블)	NMR 센서	핵 스핀	**자기장**	dc	열	픽업 코일
	NV 센터 앙상블	전자 스핀	**자기장, 전기장, 온도, 압력, 회전**	dc–GHz	광학	광학
고체 스핀 (단일 스핀)	Si 반도체의 P 도너	전자 스핀	**자기장**	dc–GHz	열	전기
	반도체 양자 점	전자 스핀	**자기장, 전기장**	dc–GHz	전기, 광학	전기, 광학
	단일 NV 센터	전자 스핀	**자기장, 전기장, 온도, 압력, 회전**	dc–GHz	광학	광학
초전도 회로	SQUID	초전류	**자기장**	dc–GHz	열	전기
	Flux 큐빗	순환 전류	**자기장**	dc–GHz	열	전기
	전하 큐빗	전하 고유상태	**전기장**	dc–GHz	열	전기
기본 입자	뮤온	뮤온 스핀	**자기장**	dc	방사성 붕괴	방사성 붕괴
	중성자	핵스핀	**자기장, 포논 밀도, 중력**	dc	브래그 산란	브래그 산란
기타 센서	SET	전하 고유상태	**전기장**	dc–MHz	열	전기
	광역학계	포논	**힘, 가속도, 질량, 자기장, 전압**	–	–	–
	간섭계	광자, (원자, 분자)	**변위, 굴절률**	–	–	–

강의 계획

- **Part 1 : 스핀 큐비트 기반 양자센싱 기초 원리**

- **Part 2 : 다이아몬드 NV 센터 소개**

- **Part 3 : NV 센터 기반 양자센싱 및 이미징 연구 소개**

Part 1 : 스핀 큐비트 기반 양자센싱 기초 원리

1.1 Qubit (Two level system)

$|1\rangle$, $|e\rangle$, $|V\rangle$, $\uparrow$ $\quad E=\hbar\omega_q$ $\quad \frac{\hbar\omega_q}{2}$

$E=\hbar\omega_q$ ···· or

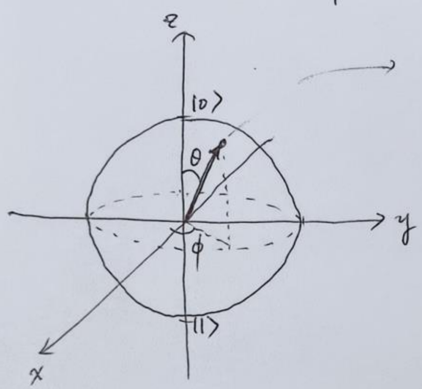
$|0\rangle$, $|g\rangle$, $|H\rangle$, $\downarrow$ $\quad E=0$ $\quad -\frac{\hbar\omega_q}{2}$

Qubit state : $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$(\ |\alpha|^2 + |\beta|^2 = 1\ )$

$\rightarrow |\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$ $\quad \phi$: relative phase

1.2. Bloch representation



$\longrightarrow |\psi\rangle = \cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2} e^{i\phi}|1\rangle$

$(\theta = 0, \cdots, \pi)$

$\begin{cases} +\hat{z} : |0\rangle \\ -\hat{z} : |1\rangle \end{cases}$, $\begin{cases} +\hat{x} : \frac{|0\rangle+|1\rangle}{\sqrt{2}} \\ -\hat{x} : \frac{|0\rangle-|1\rangle}{\sqrt{2}} \end{cases}$, $\begin{cases} +\hat{y} : \frac{|0\rangle+i|1\rangle}{\sqrt{2}} \\ -\hat{y} : \frac{|0\rangle-i|1\rangle}{\sqrt{2}} \end{cases}$

- π (180°) turn around $\hat{z}$: $|\psi\rangle \rightarrow |\psi'\rangle$

$$|\psi'\rangle = \cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2} e^{i(\phi+\pi)}|1\rangle$$

$$= \cos\frac{\theta}{2}|0\rangle - \sin\frac{\theta}{2}|1\rangle$$

$$Z \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \sigma_z$$

- π around $\hat{x}$: $|0\rangle \to |1\rangle$, $|1\rangle \to |0\rangle$

$$X \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \sigma_x$$

- π around $\hat{y}$:

$$Y \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} = \sigma_y$$

1.3. Qubit Hamiltonian

$$H = \hbar\omega_q |1\rangle\langle 1| + 0 \cdot |0\rangle\langle 0|$$

or

$$= \frac{\hbar\omega_q}{2} |1\rangle\langle 1| - \frac{\hbar\omega_q}{2} |0\rangle\langle 0|$$

$$= -\frac{\hbar\omega_q}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = -\frac{\hbar\omega_q}{2} \sigma_z$$

① time evolution

$$\frac{\partial}{\partial t}|\psi\rangle = -\frac{i}{\hbar} H |\psi\rangle \quad , H = -\frac{\hbar\omega_q}{2}\sigma_z$$

$$\rightarrow \frac{\partial}{\partial t}\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = -\frac{i}{\hbar}\left(-\frac{\hbar\omega_q}{2}\right)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix} = \begin{pmatrix} i\frac{\omega_q}{2}\alpha \\ -i\frac{\omega_q}{2}\beta \end{pmatrix}$$

$$\therefore \alpha(t) = e^{+i\frac{\omega_q}{2}t}\alpha(0) \quad , \quad \beta(t) = e^{-i\frac{\omega_q}{2}t}\beta(0)$$

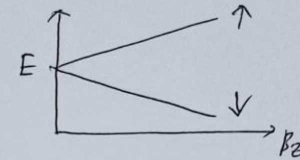
$\therefore$ precess at ω_q

"시연1"

② Zeeman splitting

—— ↑ $m_s = +\frac{1}{2}$

—— ↓ $m_s = -\frac{1}{2}$ $\Uparrow B_z$



$$H = -\frac{\hbar\omega_q}{2}\sigma_z - \frac{\hbar\gamma}{2}B_z\sigma_z$$

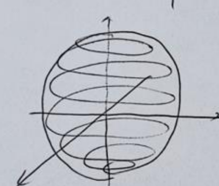
$\therefore$ precess at $\omega_q + \gamma B_z$

"1GHz" at $B_z = 100$ Gauss

③ Driving with $H_\perp(x,y)$

$E = \hbar\omega_q$ ω, Ω , $H = -\frac{\hbar\omega_q}{2}\sigma_z + \hbar\Omega\cos\omega t\,\sigma_x$

time evolution: $i\hbar\frac{d}{dt}\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = \begin{pmatrix}-\frac{\hbar\omega_q}{2}\alpha\\ +\frac{\hbar\omega_q}{2}\beta\end{pmatrix} + \hbar\Omega\cos\omega t\begin{pmatrix}\beta\\ \alpha\end{pmatrix}$



at lab frame,

precess freq $\sim \omega_q(\omega)$ (fast)

$\uparrow \rightleftharpoons \downarrow$ freq $\sim \Omega$ (slow)

Go into "rotating frame"

$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = \begin{pmatrix}\tilde{\alpha}\, e^{+i\frac{\omega}{2}t}\\ \tilde{\beta}\, e^{-i\frac{\omega}{2}t}\end{pmatrix}$$

$$\rightarrow \underbrace{i\hbar\left(+i\frac{\omega}{2}\right)}_{=-\frac{\hbar\omega}{2}}\begin{pmatrix}\tilde{\alpha}\, e^{i\frac{\omega}{2}t}\\ -\tilde{\beta}\, e^{-i\frac{\omega}{2}t}\end{pmatrix} + i\hbar\begin{pmatrix}\dot{\tilde{\alpha}}\, e^{i\frac{\omega}{2}t}\\ \dot{\tilde{\beta}}\, e^{-i\frac{\omega}{2}t}\end{pmatrix}$$

$$(\cos\omega t)\,\beta = \frac{1}{2}\left(e^{i\omega t} + e^{-i\omega t}\right)\tilde{\beta}\, e^{-i\frac{\omega}{2}t}$$

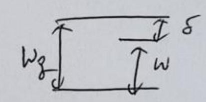
$$= \frac{1}{2}\Big(e^{i\frac{\omega}{2}t} + \underbrace{e^{-i\frac{3\omega}{2}t}}_{\approx 0 \ \because\ \text{RWA (Rotating Wave Approx.)}} \Big)\tilde{\beta} \approx \frac{1}{2} e^{i\frac{\omega}{2}t}\tilde{\beta}$$

$$\rightarrow \quad \approx -\frac{\hbar\omega_z}{2}\begin{pmatrix} \tilde{\alpha}\, e^{+i\frac{\omega}{2}t} \\ -\tilde{\beta}\, e^{-i\frac{\omega}{2}t} \end{pmatrix} + \frac{\hbar\Omega}{2}\begin{pmatrix} \tilde{\beta}\, e^{+i\frac{\omega}{2}t} \\ \tilde{\alpha}\, e^{-i\frac{\omega}{2}t} \end{pmatrix}$$

$$\xrightarrow{\text{cancel } e^{\pm i\frac{\omega}{2}t}} \quad i\hbar\begin{pmatrix} \dot{\tilde{\alpha}} \\ \dot{\tilde{\beta}} \end{pmatrix} = -\left(\frac{\hbar\omega_z}{2} - \frac{\hbar\omega}{2}\right)\begin{pmatrix} \tilde{\alpha} \\ -\tilde{\beta} \end{pmatrix} + \frac{\hbar\Omega}{2}\begin{pmatrix} \tilde{\beta} \\ \tilde{\alpha} \end{pmatrix}$$

$$= -\frac{\hbar\delta}{2}\sigma_z\begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \end{pmatrix} + \frac{\hbar\Omega}{2}\sigma_x\begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \end{pmatrix}$$

($\delta \equiv \omega_z - \omega$, detuning



)

$$= \tilde{H}\begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \end{pmatrix}, \quad \tilde{H} = -\frac{\hbar\delta}{2}\sigma_z + \frac{\hbar\Omega}{2}\sigma_x$$

on resonance , $\delta = 0$

$$i\hbar\begin{pmatrix} \dot{\tilde{\alpha}} \\ \dot{\tilde{\beta}} \end{pmatrix} = \frac{\hbar\Omega}{2}\sigma_x\begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \end{pmatrix}$$

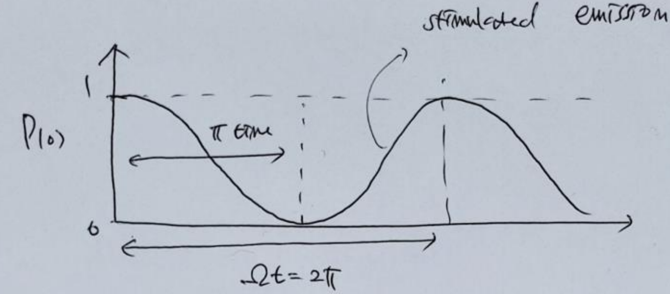
rotates around $\hat{x}$ at freq of $\hbar\Omega$

—— $|1\rangle$, $P_{|1\rangle}$

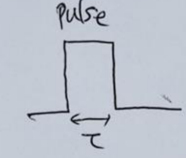
—— $|0\rangle$, $P_{|0\rangle}$

$$\langle\sigma_z\rangle = P_{|0\rangle} - P_{|1\rangle} = P_{|0\rangle} - (1 - P_{|0\rangle}) = 2P_{|0\rangle} - 1$$

$$\therefore \quad P_{|0\rangle}(t) = \frac{1}{2}\left(1 + \langle\sigma_z\rangle\right) = \frac{1}{2}\left(1 + \cos\Omega t\right)$$



$\left(\begin{array}{l} \text{Rabi oscillation} \\ \Omega : \text{Rabi freq.} \end{array} \right.$



$$\begin{cases} \Omega\tau = \pi & : \text{“}\pi\text{-pulse”} \\ \Omega\tau = \frac{\pi}{2} & : \text{“}\frac{\pi}{2}\text{-pulse”} \end{cases}$$

$$\left. \begin{array}{l} |0\rangle \xrightarrow[\frac{\pi}{2}y]{} \frac{|0\rangle+|1\rangle}{\sqrt{2}} \\ |1\rangle \xrightarrow[\frac{\pi}{2}y]{} \frac{|0\rangle-|1\rangle}{\sqrt{2}} \end{array} \right) \to \underbrace{\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}}\begin{pmatrix} |0\rangle \\ |1\rangle \end{pmatrix}$$

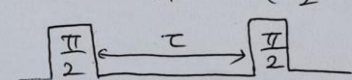
$\equiv H$ (Hadamard) gate

"AQ3"

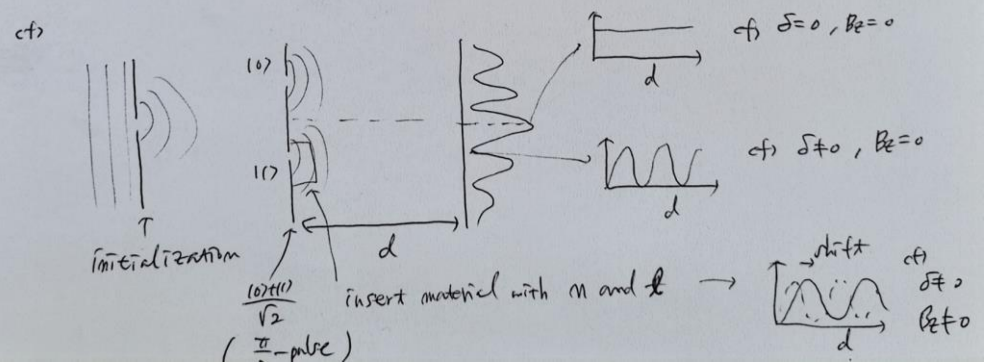
④ Ramsey interferometry (DC field sensing)

$$H = -\frac{\hbar\omega_z}{2}\sigma_z - \frac{\hbar\gamma}{2}B_z\sigma_z$$

rotating frame $\longrightarrow$ $\tilde{H} = -\left(\frac{\hbar\delta}{2} + \frac{\hbar\gamma}{2}B_z\right)\sigma_z$ "AQ4_Ramsey"

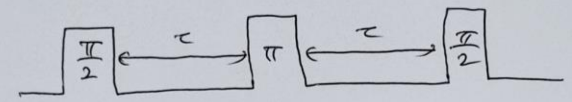


cf)

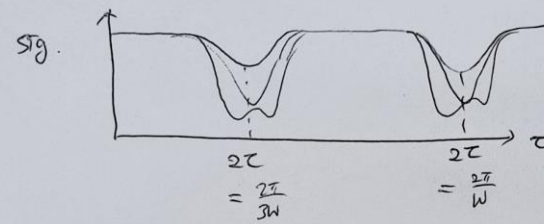


⑤ (spin) Hahn echo (AC field sensing)

$$\tilde{H} = -\frac{\hbar\delta}{2}\sigma_z - \frac{\hbar\gamma}{2}B_z\sin(\omega t+\phi)\sigma_z$$

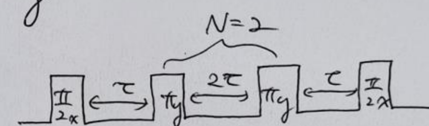


"Ant-echo"

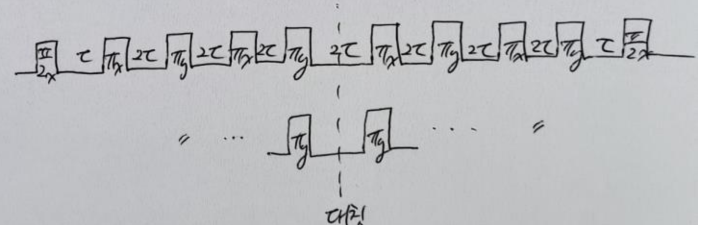


⑥ Dynamical decoupling

- CPMG (-N)
  (Car-Purcell-Meiboom-Gill)

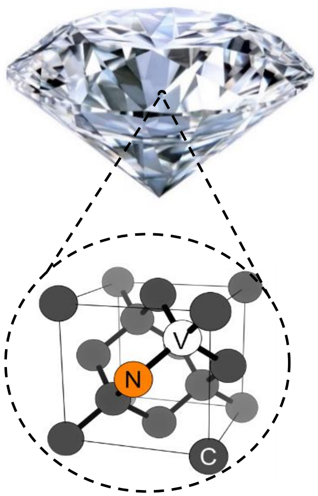


- XY-4
- XY-8



Part 2 : 다이아몬드 NV 센터 소개

Nitrogen-vacancy (NV) defect centers in diamond



Quantum Point Defects (QPDs)

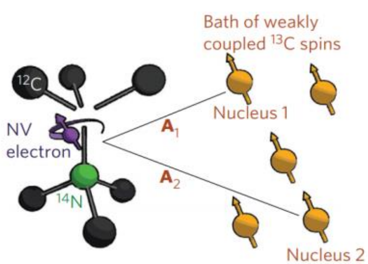
“trapped ions” in solids

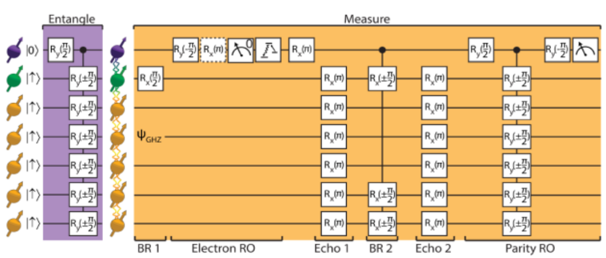
- long coherence time
- atomic size
- optically addressable
- room temperature operation

defects in semiconductors

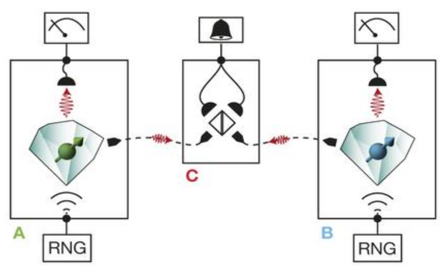
- fast manipulation
- nano fabrication
- scalable
- integrated, devices on-chip

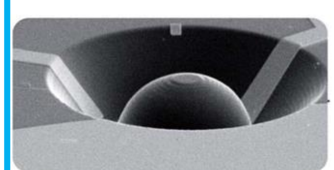
Quantum computation

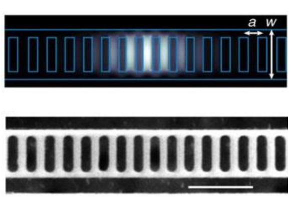




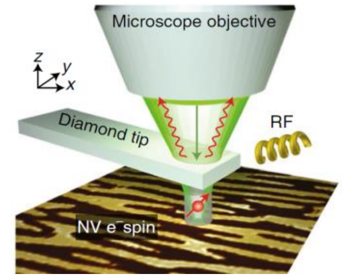
Quantum communication

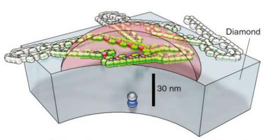


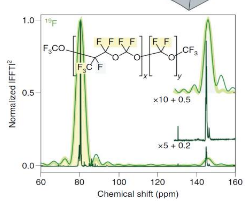


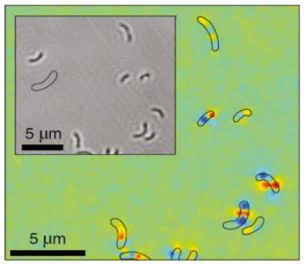


Quantum sensing

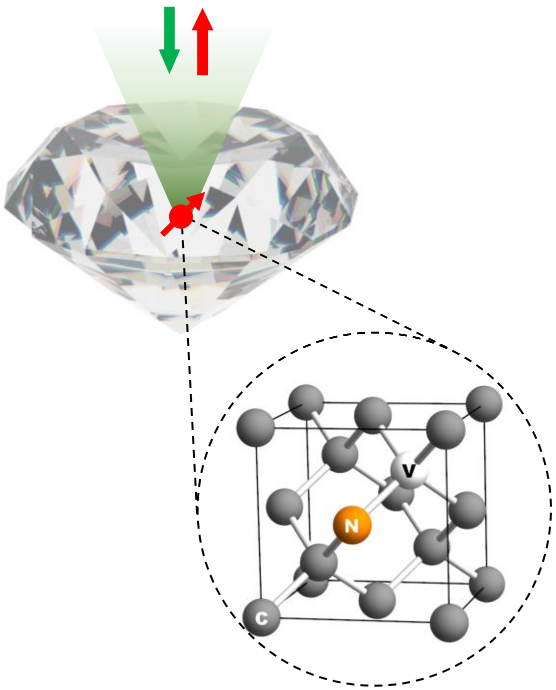


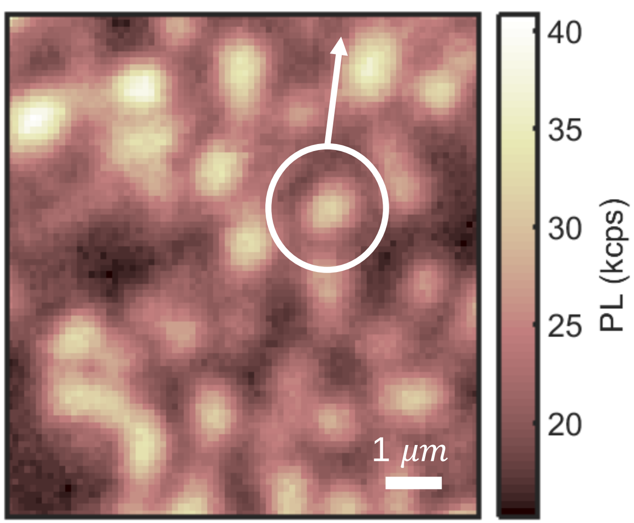






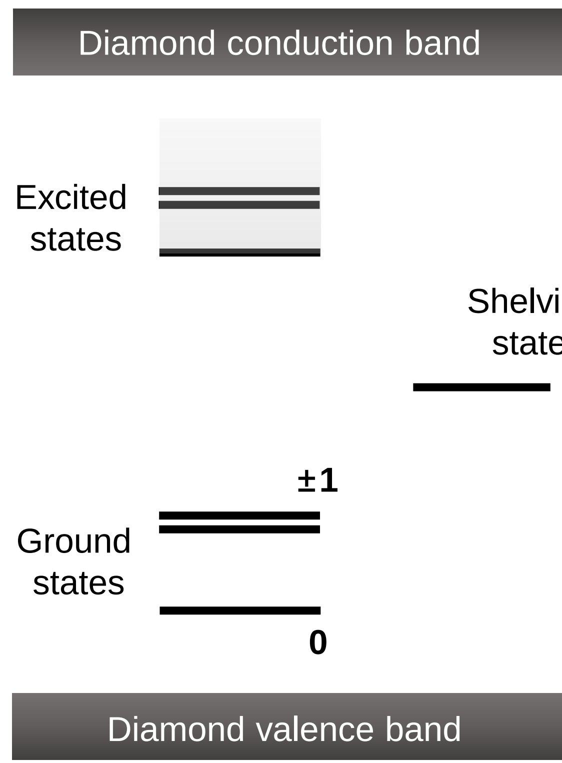
Nitrogen-vacancy (NV) defect centers in diamond



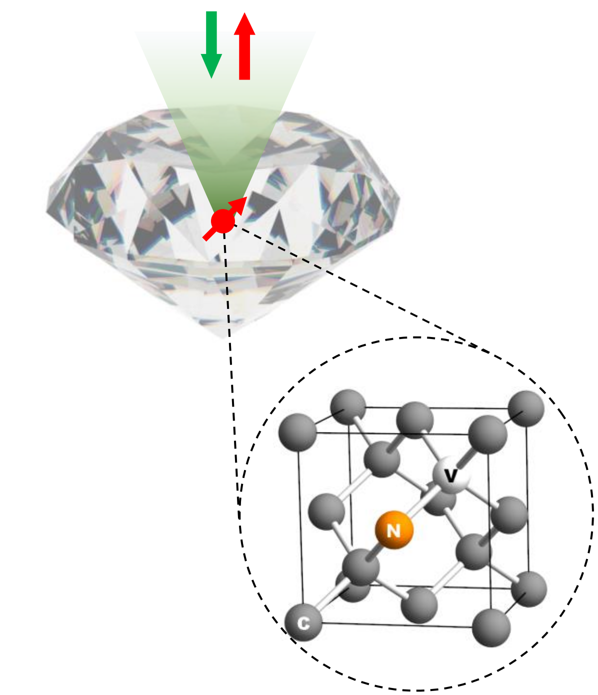


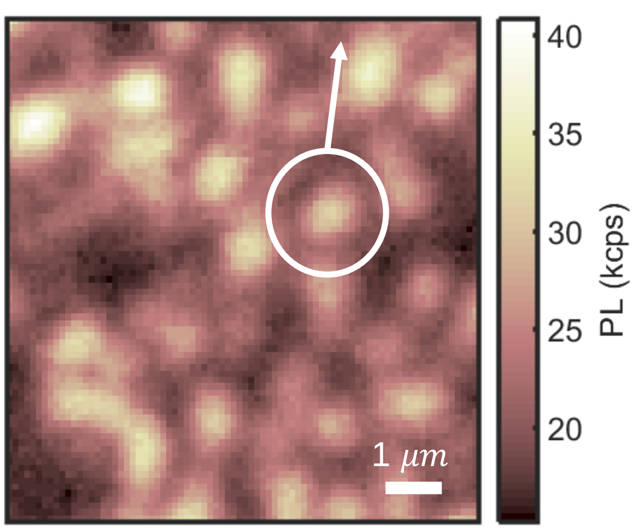
NV defect centers in diamond

- S = 1 ground states i.e. $m_s = 0$, $m_s = \pm 1$
- Spin levels are very sensitive to external magnetic field
- Magnetic signal is optically detected (ODMR)



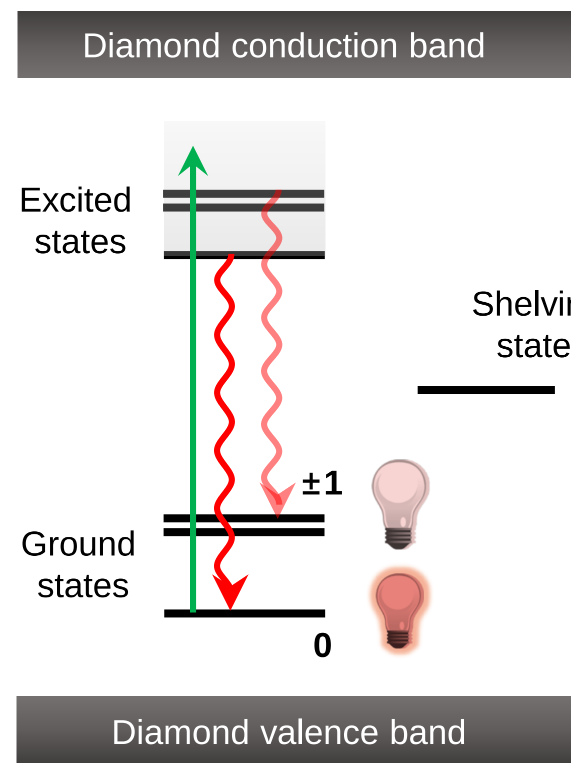
Nitrogen-vacancy (NV) defect centers in diamond





<u>NV defect centers in diamond</u>

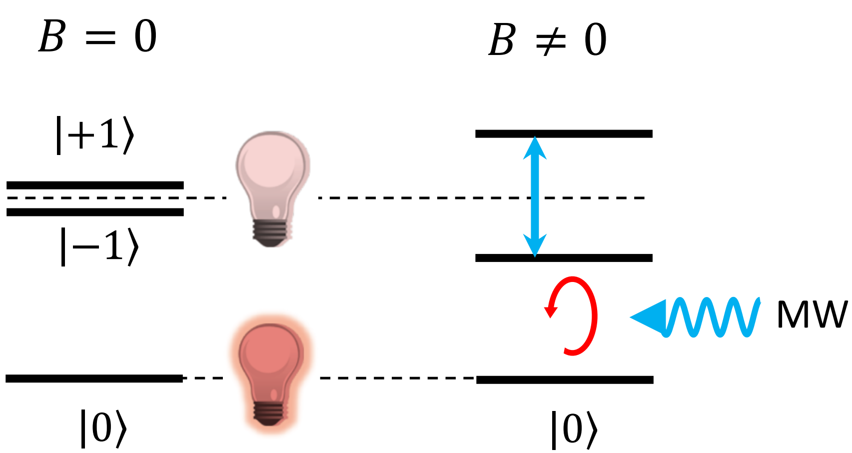
- S = 1 ground states i.e. $m_s = 0, \;\; m_s = \pm 1$
- Spin levels are very sensitive to external magnetic field
- Magnetic signal is optically detected (ODMR)

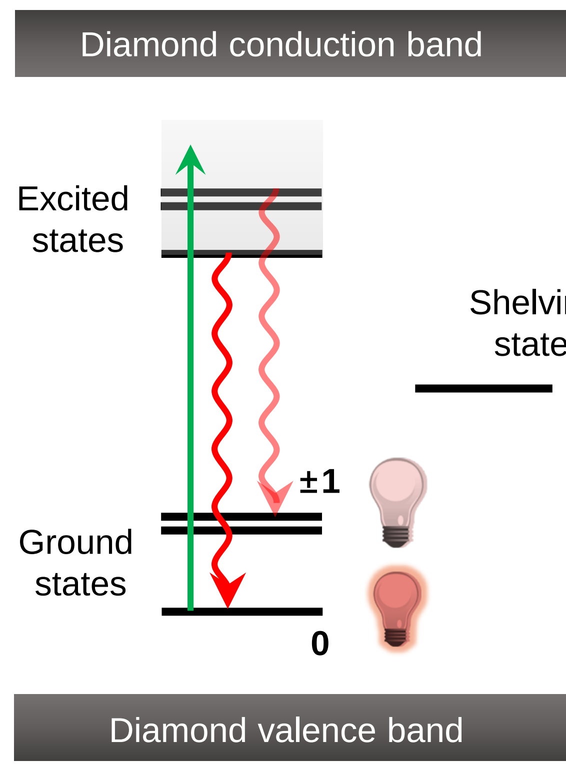


Nitrogen-vacancy (NV) defect centers in diamond

<u>NV defect centers in diamond</u>

- S = 1 ground states i.e. $m_s = 0, \ \ m_s = \pm 1$
- Spin levels are very sensitive to external magnetic field
- Magnetic signal is optically detected (ODMR)



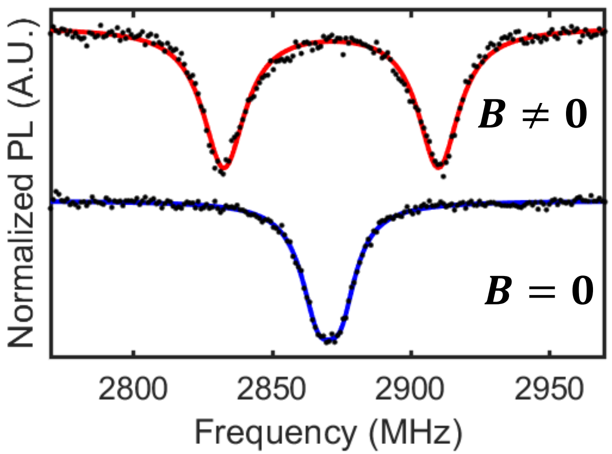


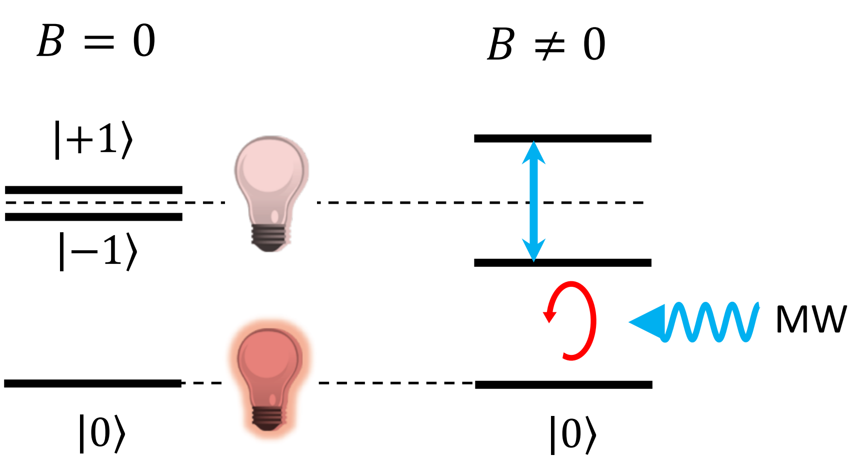
Nitrogen-vacancy (NV) defect centers in diamond

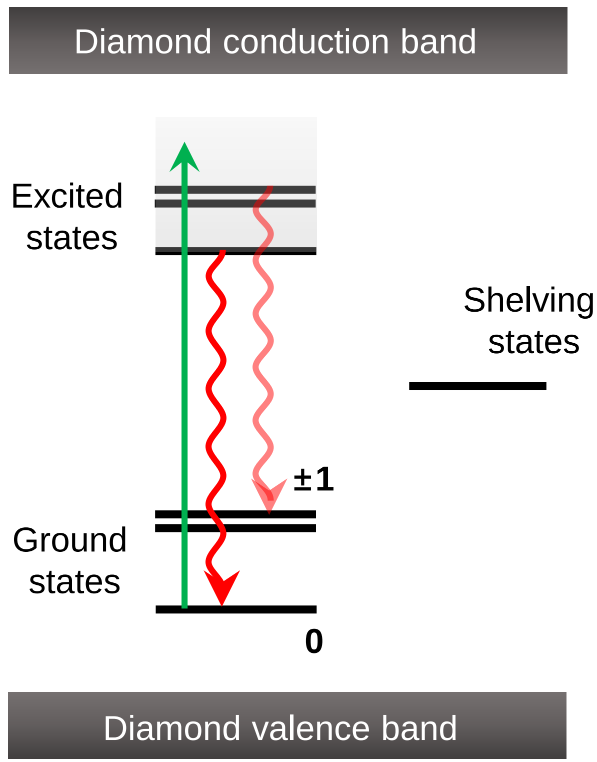
NV defect centers in diamond

- S = 1 ground states i.e. $m_s = 0, \;\; m_s = \pm 1$
- Spin levels are very sensitive to external magnetic field
- Magnetic signal is optically detected (ODMR)

Optically-detected ESR

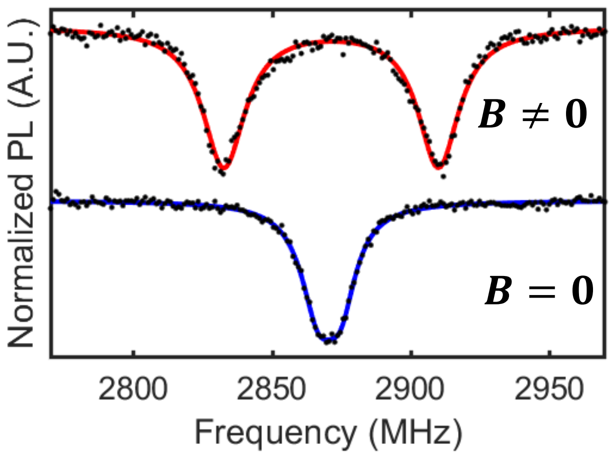


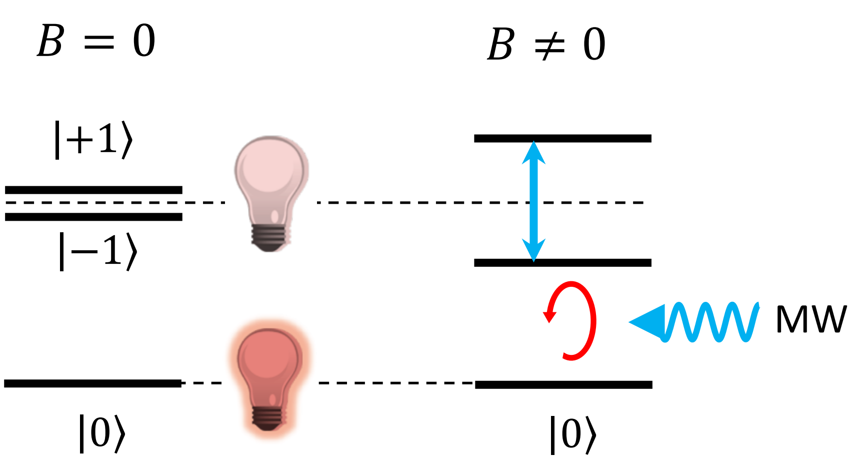




Nitrogen-vacancy (NV) defect centers in diamond

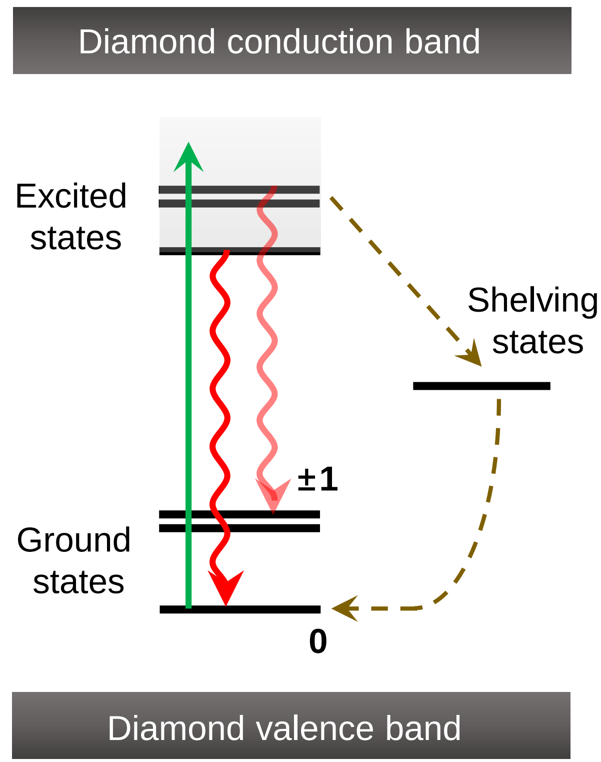
Optically-detected ESR





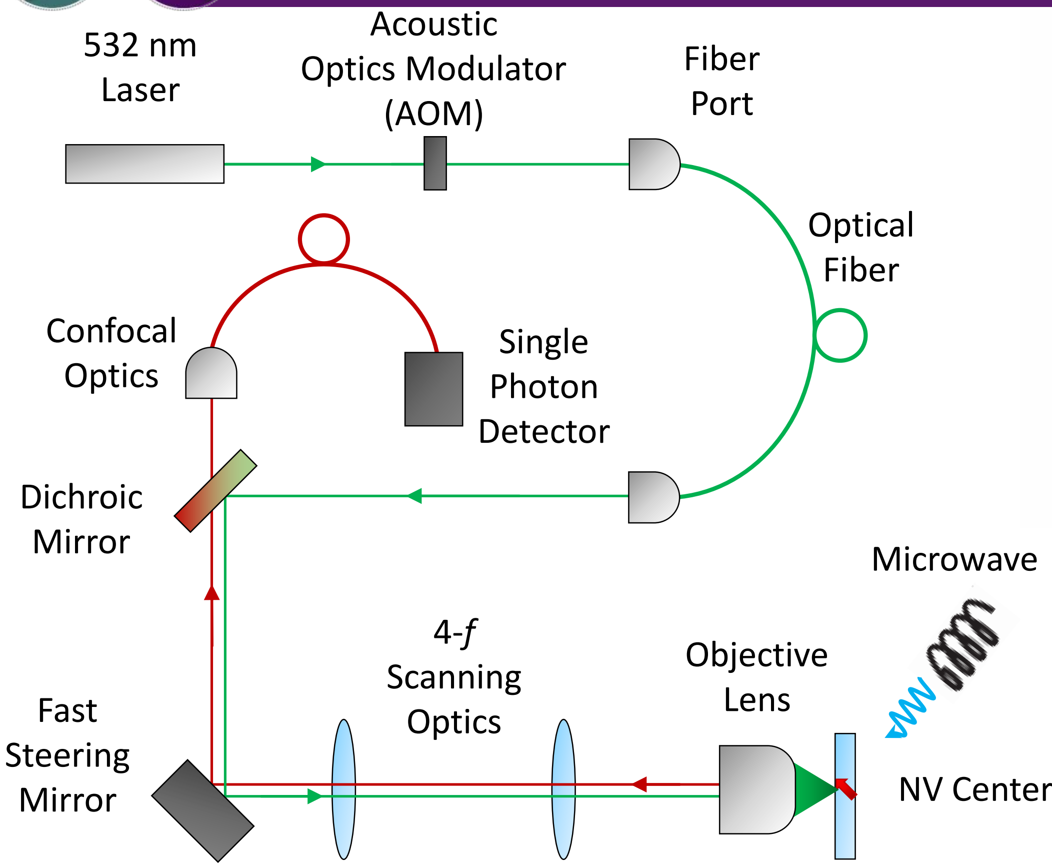
NV defect centers in diamond

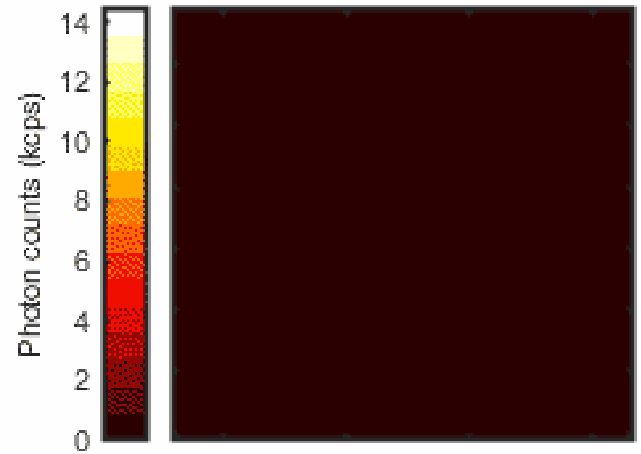
- S = 1 ground states i.e. $m_s = 0, \ m_s = \pm 1$
- Spin levels are very sensitive to external magnetic field
- Magnetic signal is optically detected (ODMR)

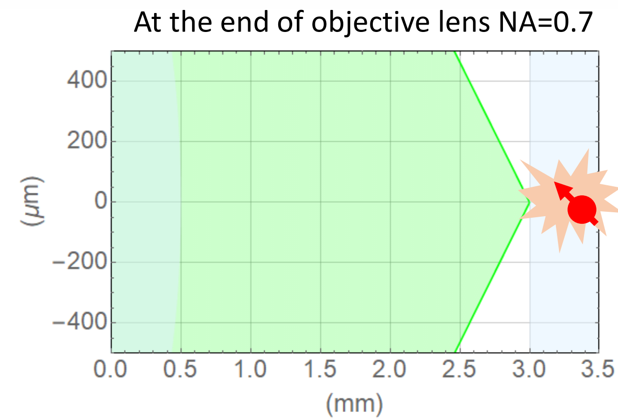


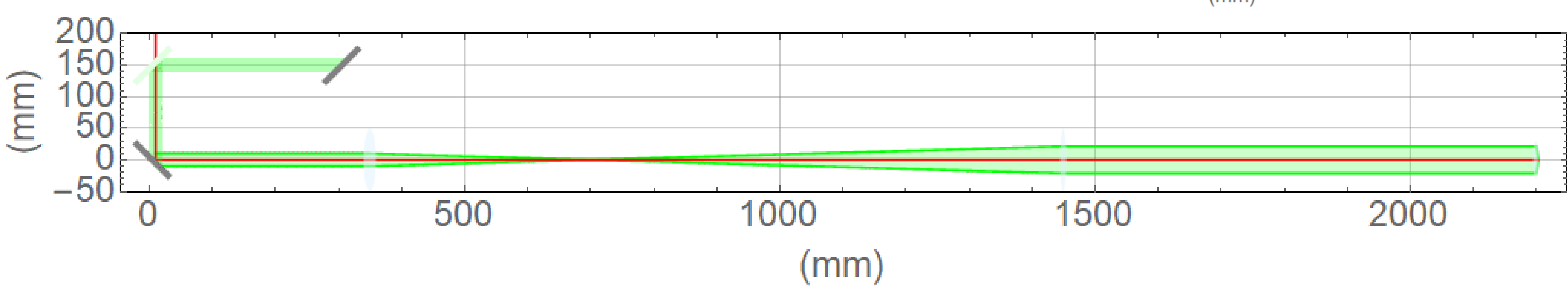
Readout & Initialization by laser

Experimental confocal optics setup









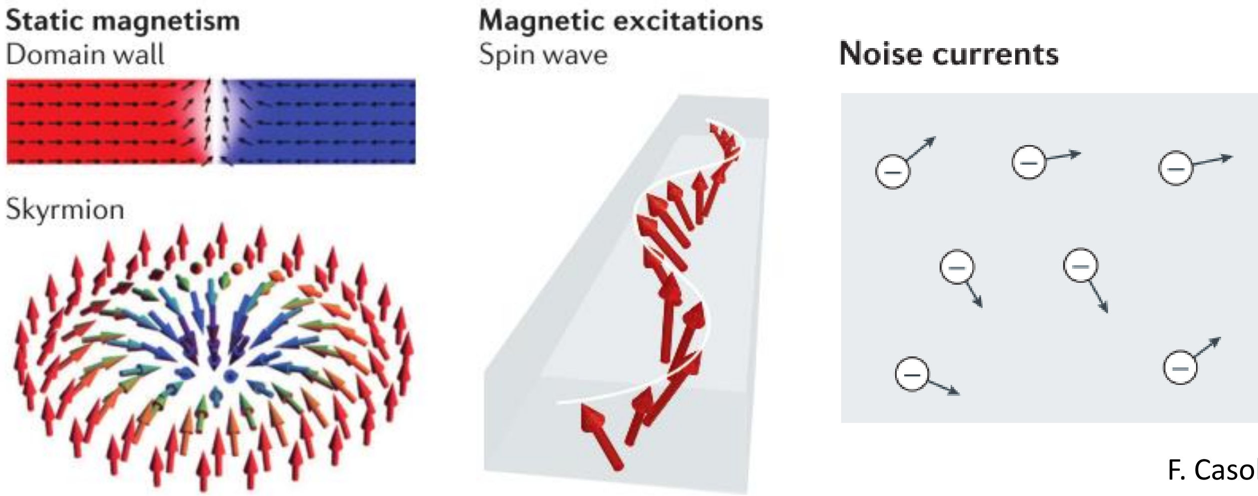
Sensitivitiy of diamond NV center

Physical property	Sensitivity	Physical property	Sensitivity	References
Magnetic field	< 1 $nT/Hz^{1/2}$ (single NV) < 1 $pT/Hz^{1/2}$ (ensemble)	Temperature	< 1 $mK/Hz^{1/2}$	J. Taylor et al., Nat. Phys. 2008 T. Wolf et al., PRX 2015 F. Dolde et al., PRL 2014 K. Lee et al., PR Applied 2016 G. Kuscko et al., Nature 2013 A. Ajoy et al., PRA 2012 M. Doherty et al., PRL 2014 R. Schirhagl et al., Ann. Rev. Phys. Chem. 2014
Electric field	< 100 $Vcm^{-1}/Hz^{1/2}$	Rotation	< 1 mdeg $/Hz^{1/2}$	
Strain field	< $10^{-7}/Hz^{1/2}$	Pressure	< 0.1 $MPa/Hz^{1/2}$	

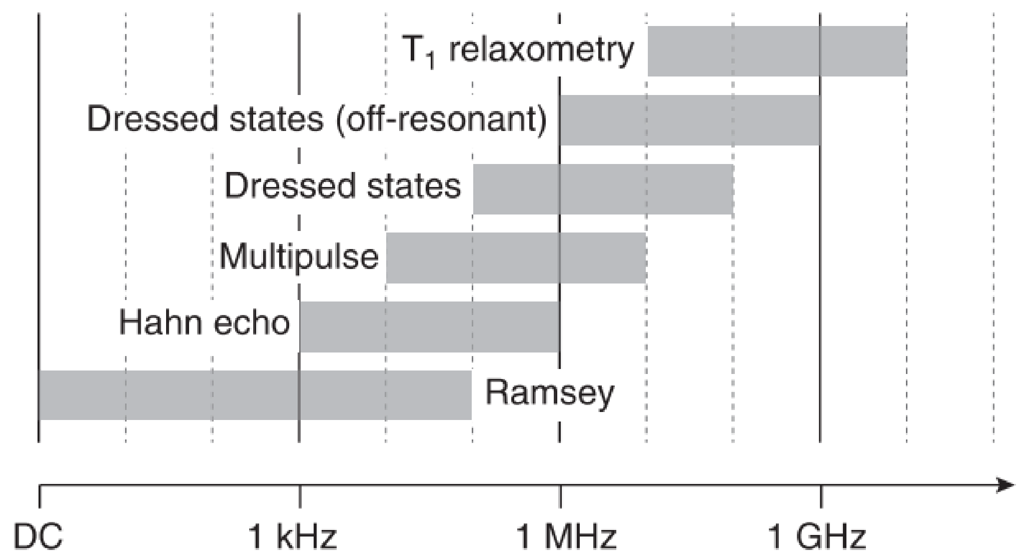
Spatial resolution	~ 10 nm	Detection bandwidth	DC – GHz	Operating temperature	Sub K to RT
Other advantages	• chemically stable, non-toxic and bio-friendly • optically stable (free from photobleaching) • suitable for devices (nano fabrication)				

Part 3 : NV 센터 기반 양자센싱 및 이미징 연구 소개

Quantum sensing examples

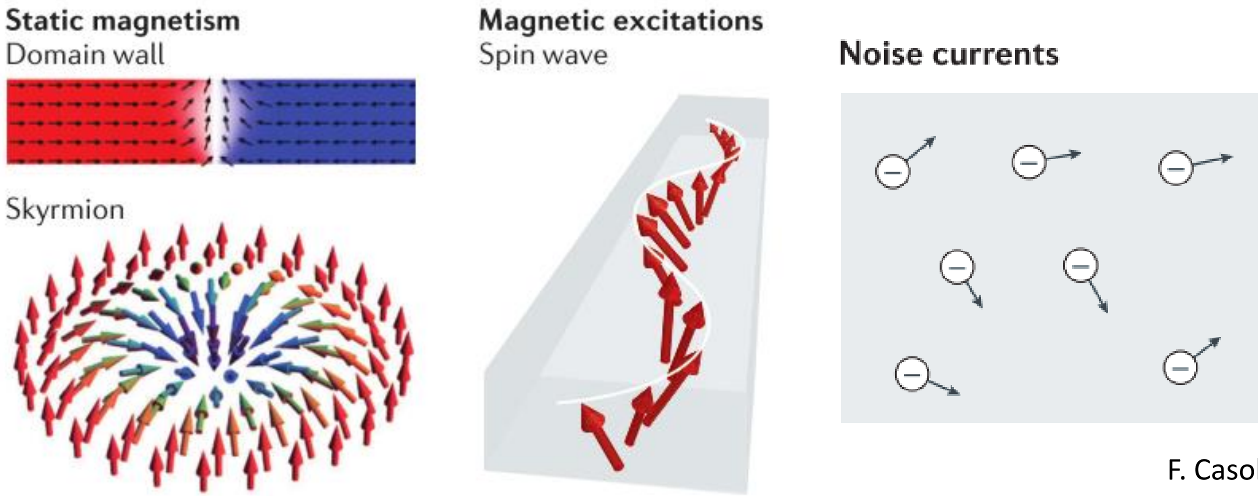


F. Casola *et al.*, Nat. Rev. Mater. (2018)

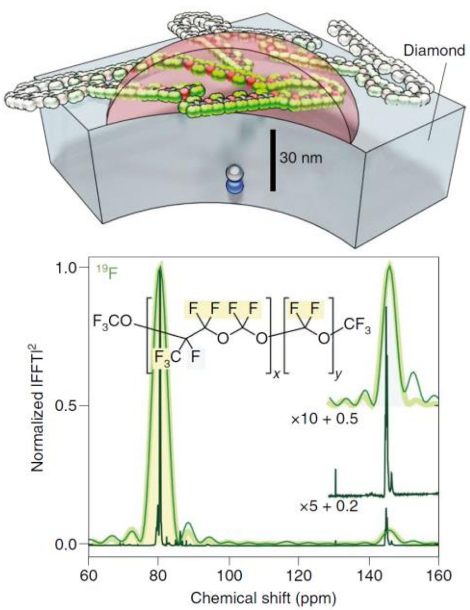


C. Degen *et al.*, Rev. of Mod. Phys. (2017)

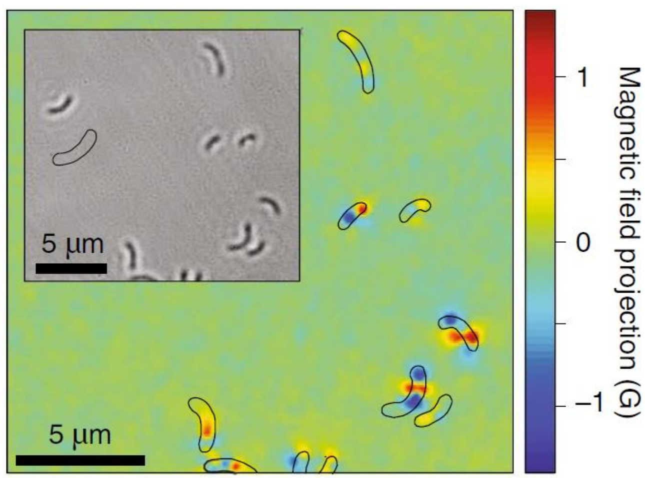
Quantum sensing examples



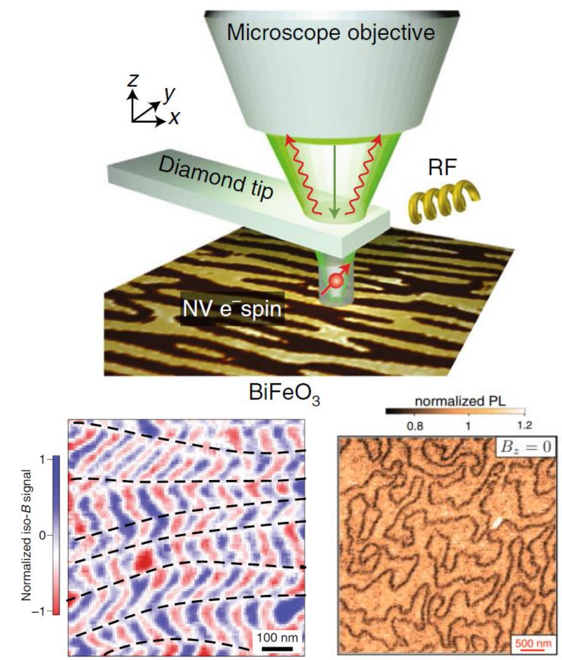
F. Casola *et al.*, Nat. Rev. Mater. (2018)



N. Aslam et al. Science 2017

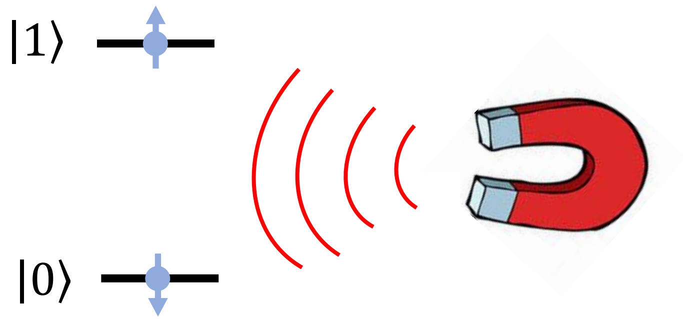


Le Sage et al. Nature 2013

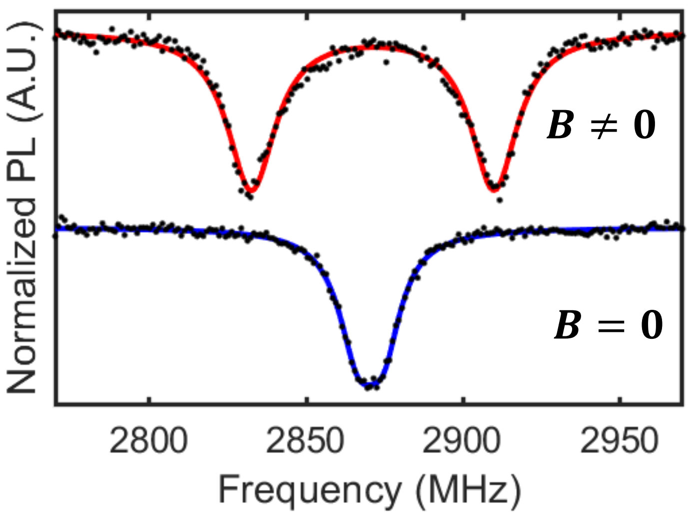


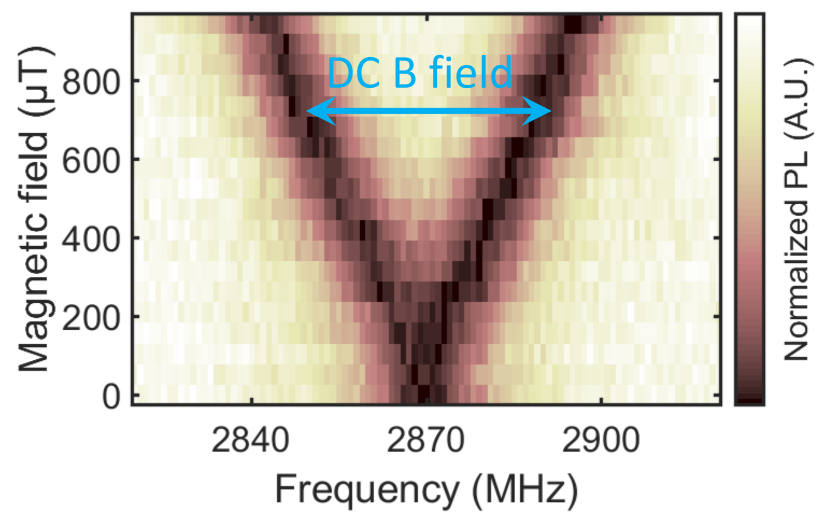
I. Gross et al. Nature 2017

Sensing static (DC) B field

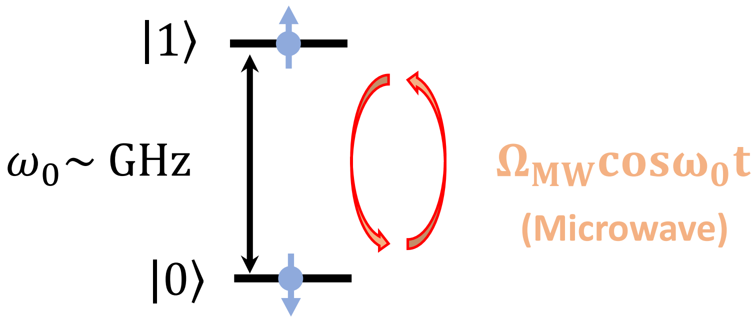


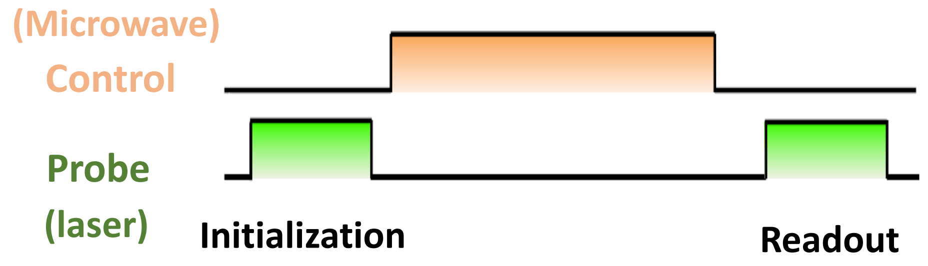
Optically-detected ESR

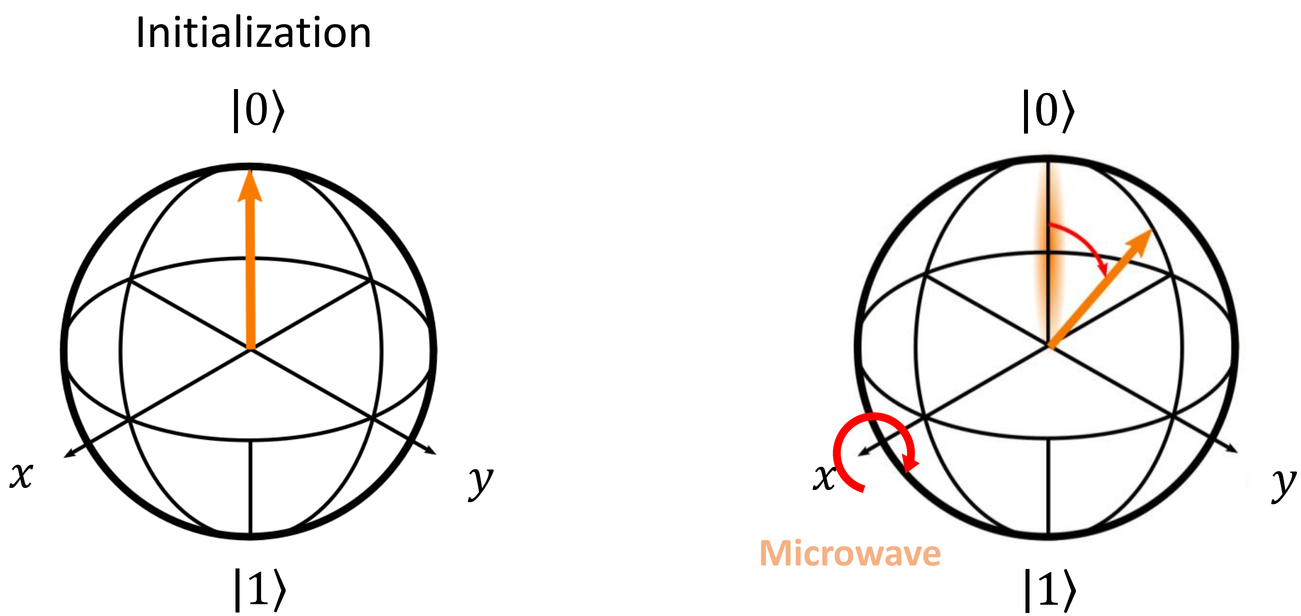




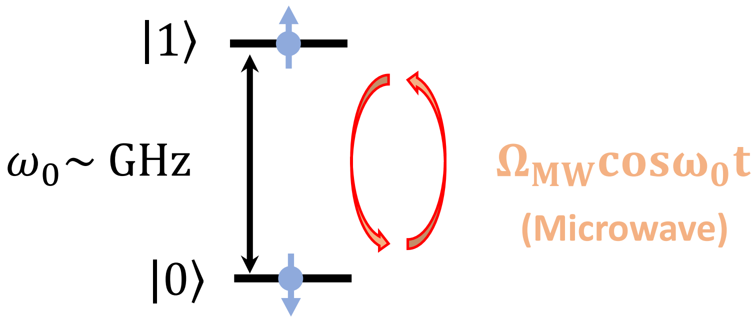
Sensing static (DC) B field



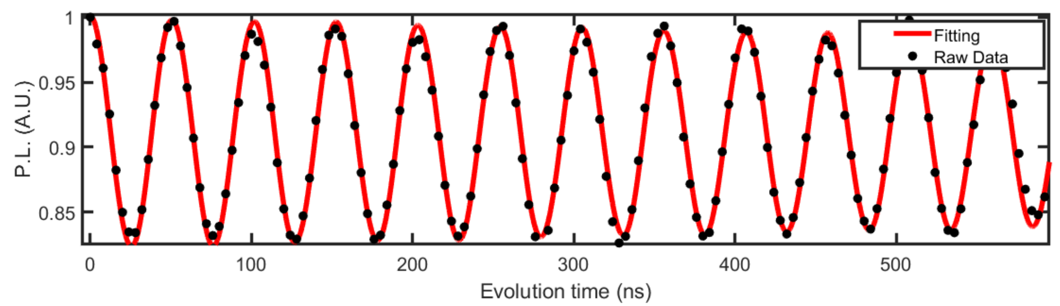




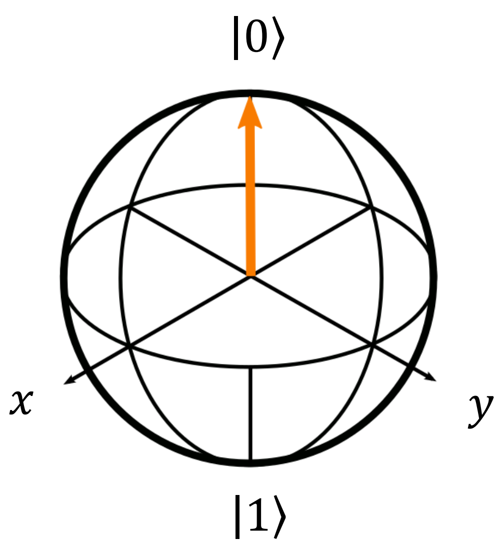
Sensing static (DC) B field

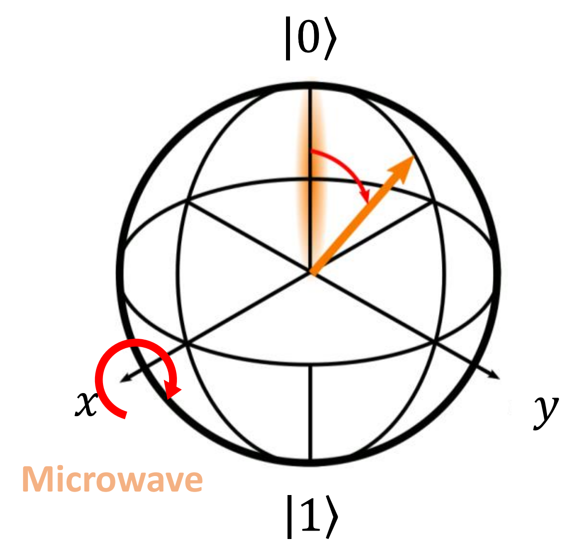


Rabi oscillation

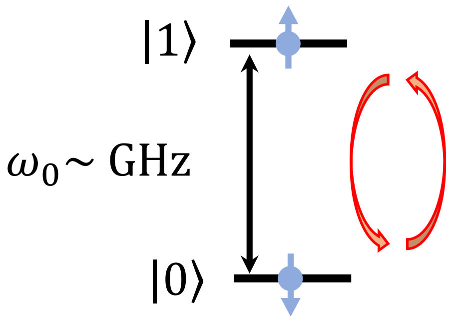


Initialization



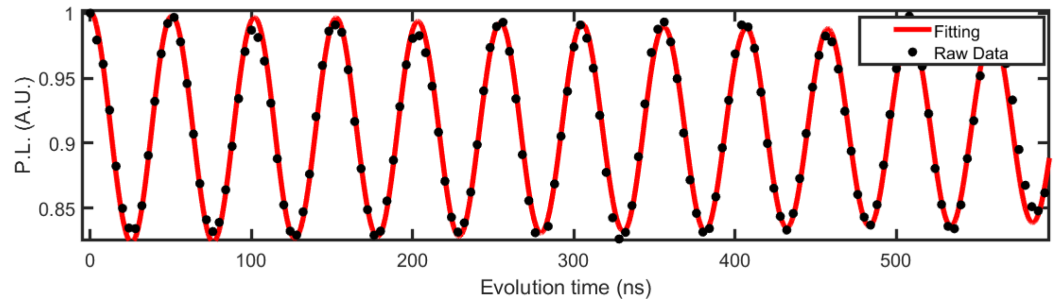


Sensing static (DC) B field

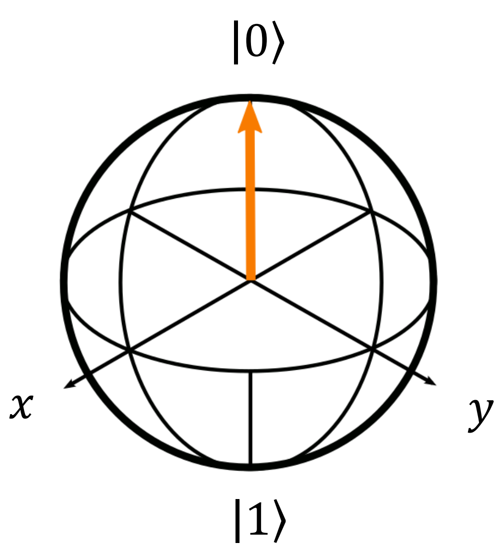


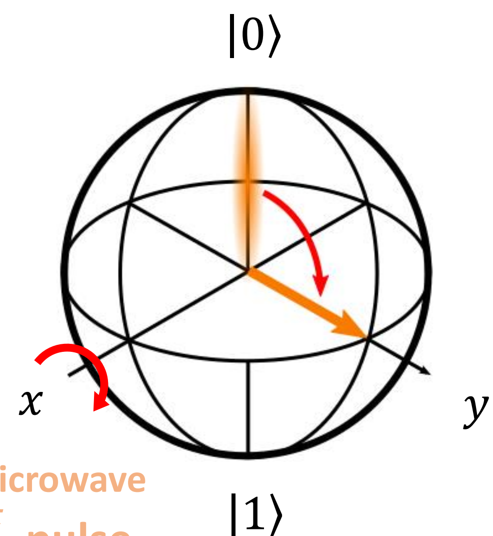
$\Omega_{MW}\cos\omega_0 t$
(Microwave)

Rabi oscillation



Initialization





Microwave
$\frac{\pi}{2}$ pulse

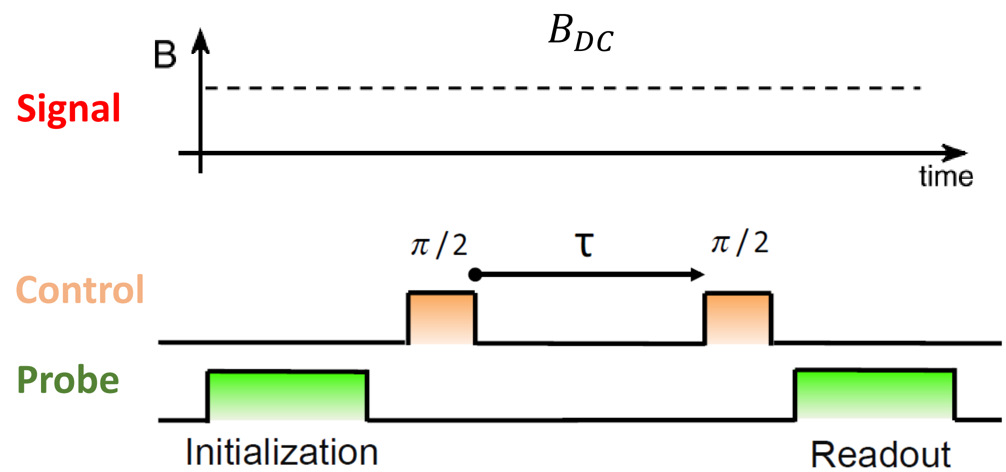
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Sensing static (DC) B field

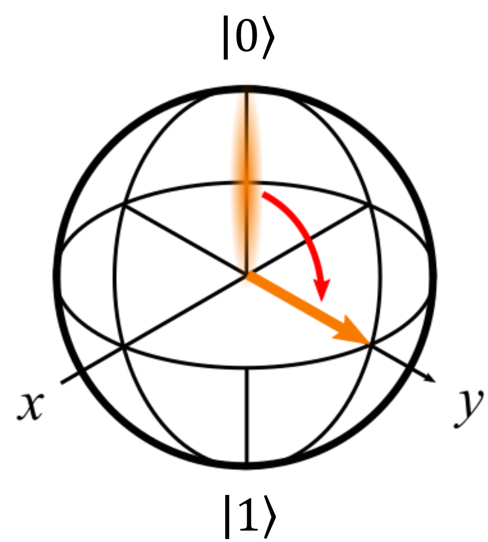
Ramsey Interferometry

$|1\rangle$

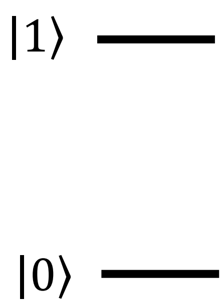
$|0\rangle$



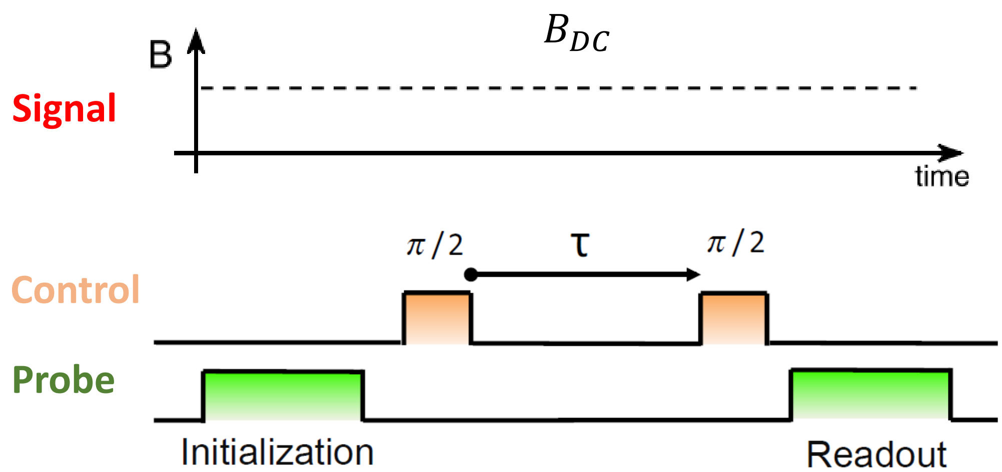
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



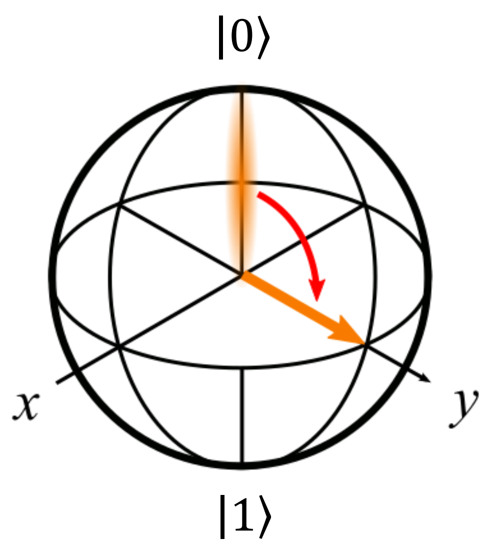
Sensing static (DC) B field



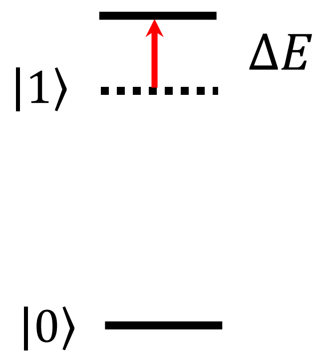
Ramsey Interferometry



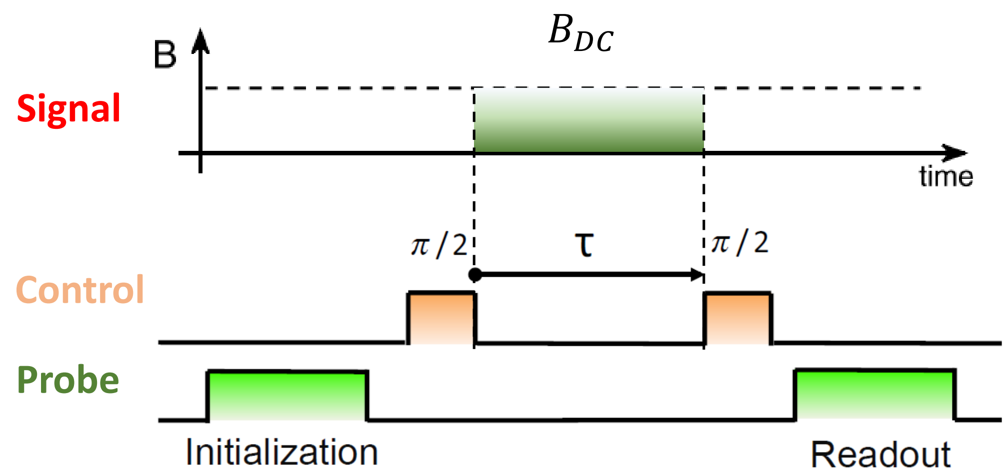
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

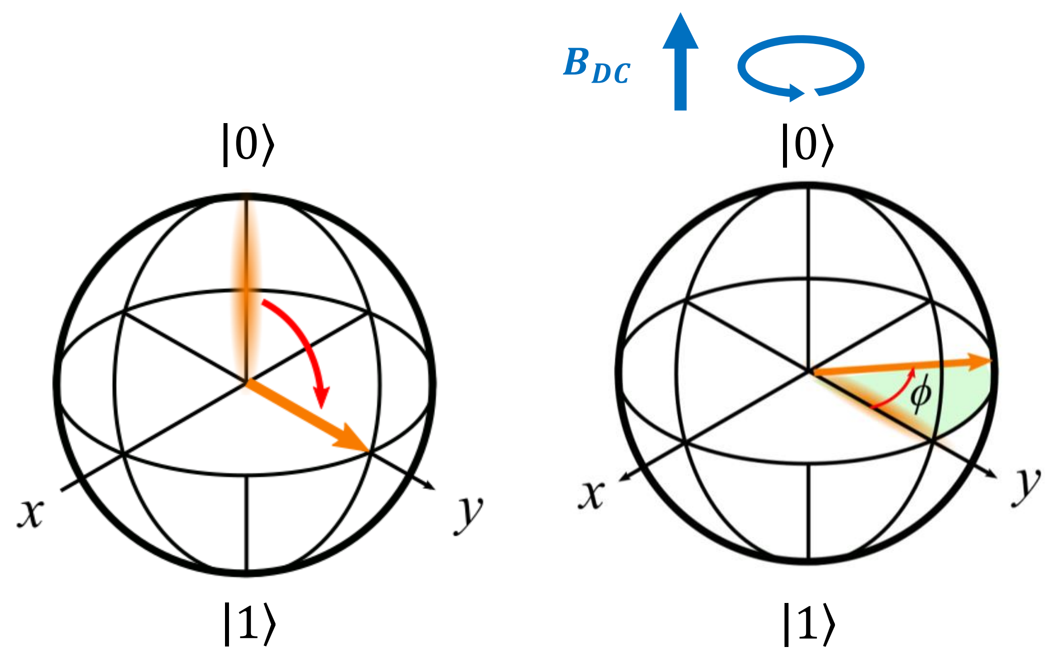


Sensing static (DC) B field



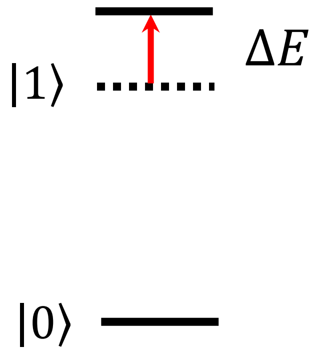
Ramsey Interferometry



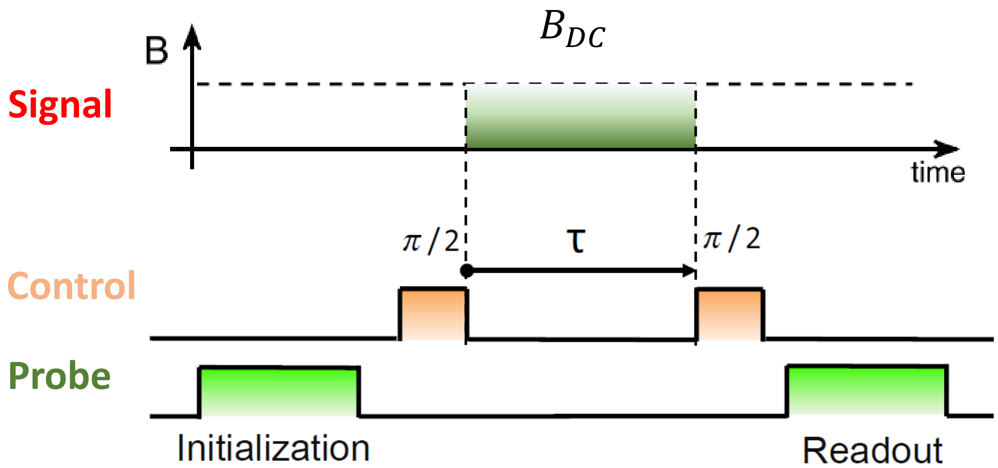


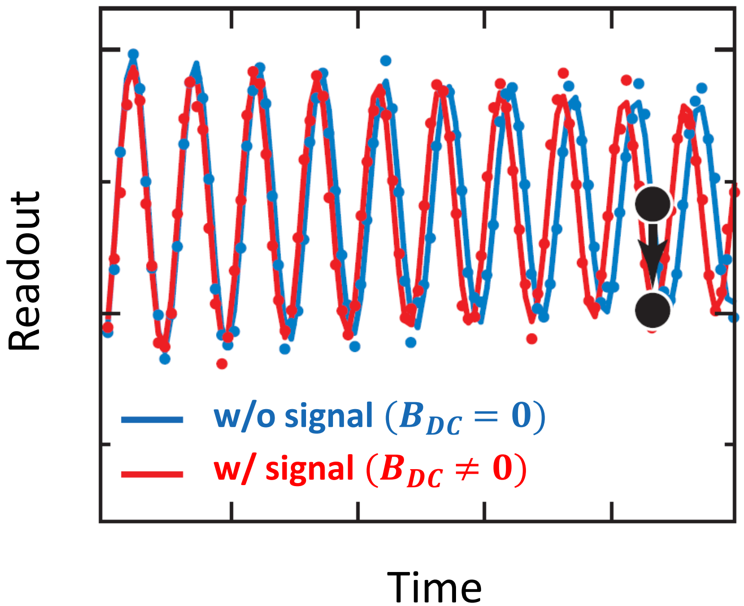
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$$

Sensing static (DC) B field

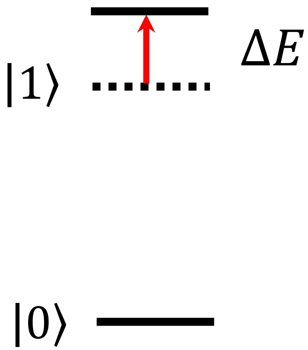


Ramsey Interferometry

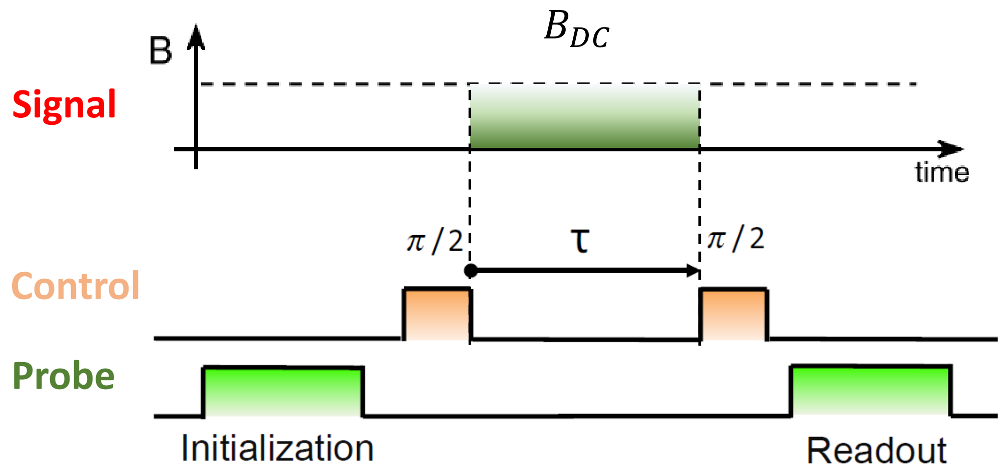


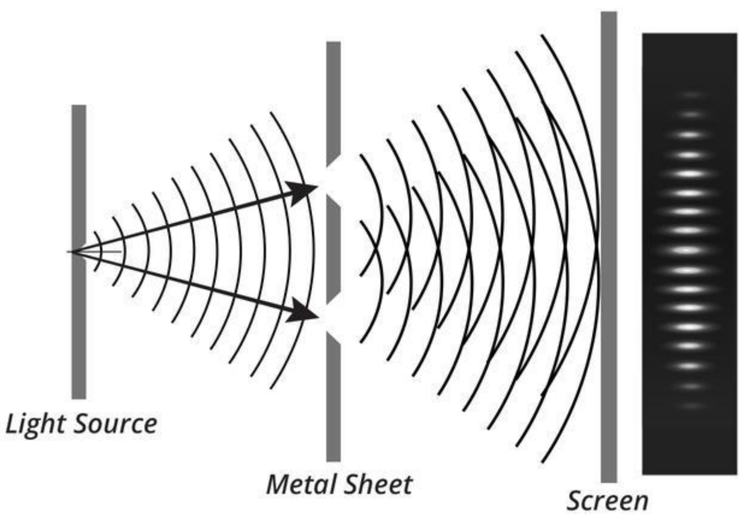


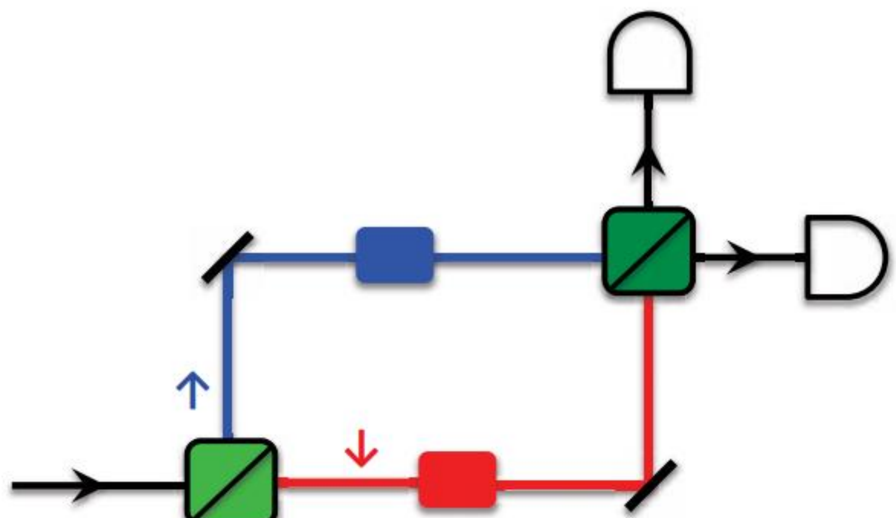
Sensing static (DC) B field



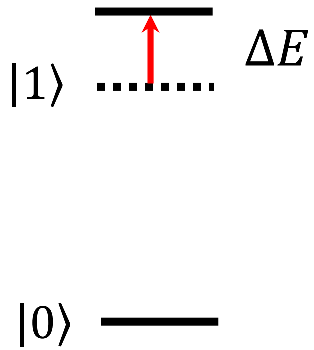
Ramsey Interferometry



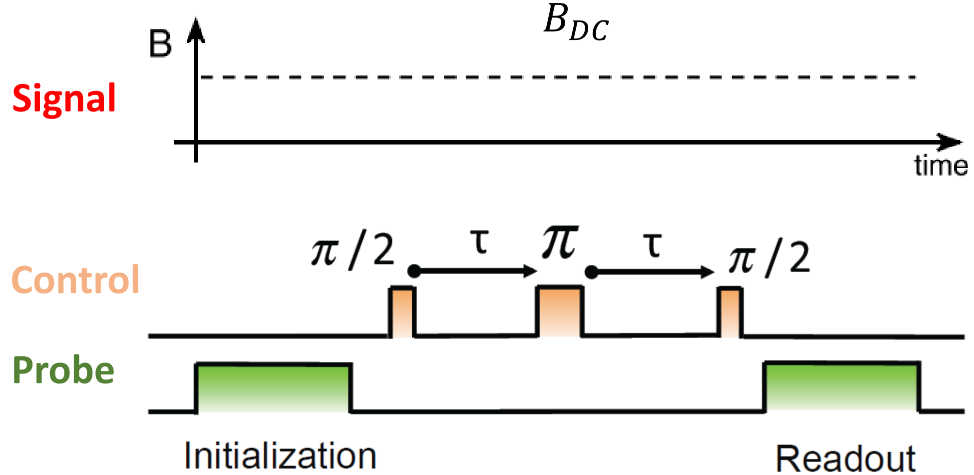


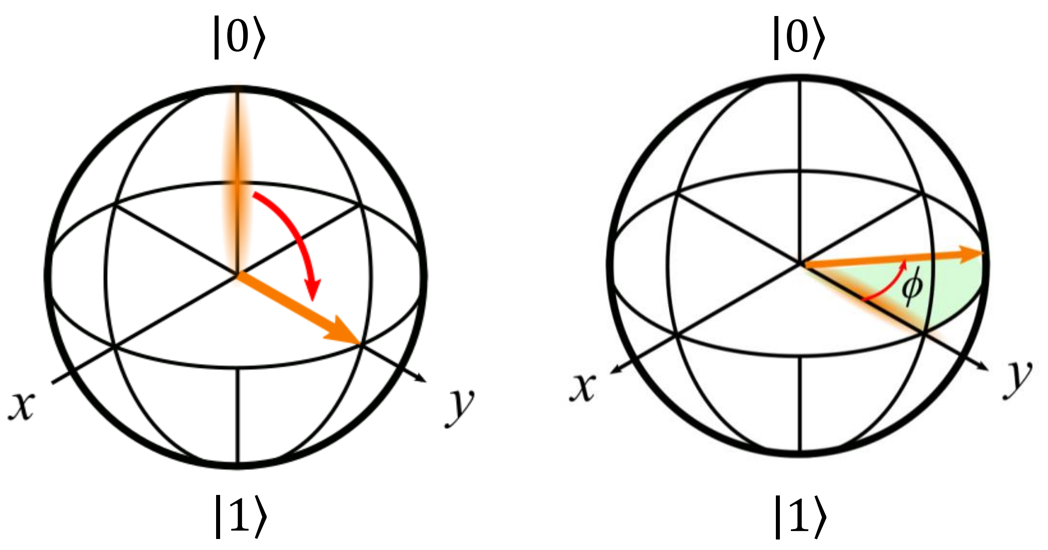


Sensing dynamics (AC) B field

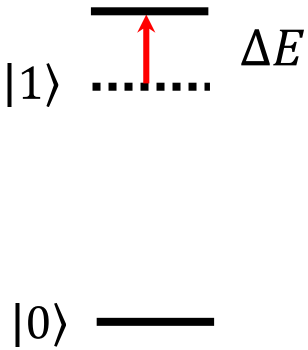


<u>spin Hahn echo</u>

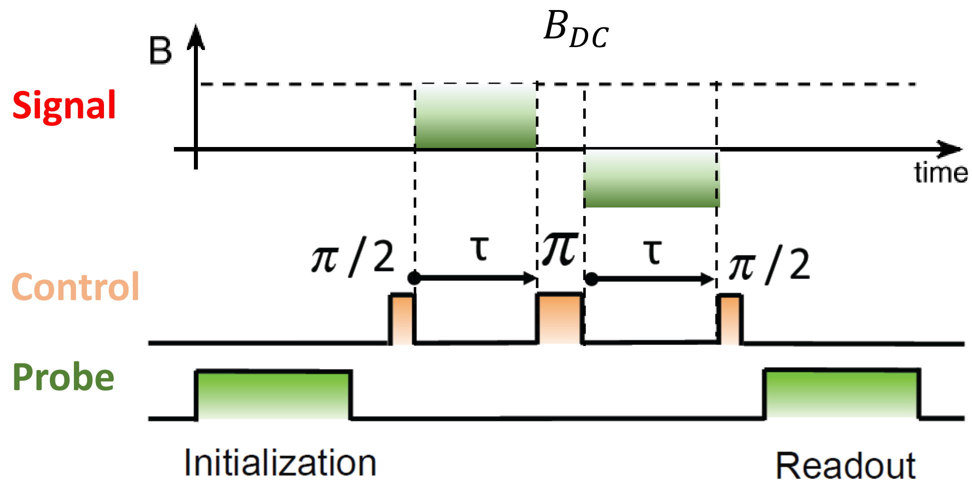




Sensing dynamics (AC) B field



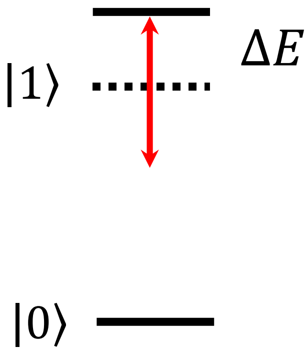
spin Hahn echo



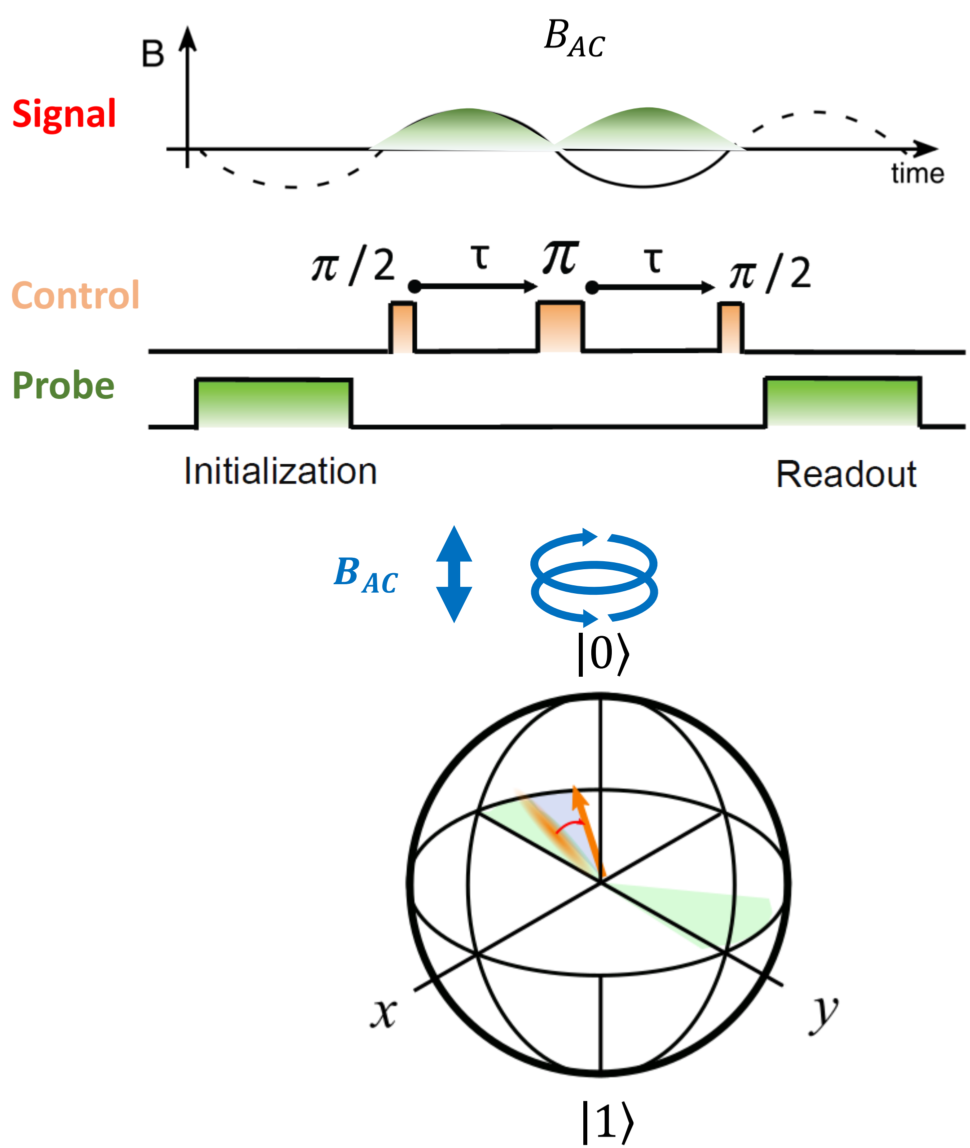
$$\phi = \phi_1 - \phi_2 = 0$$

for DC signal

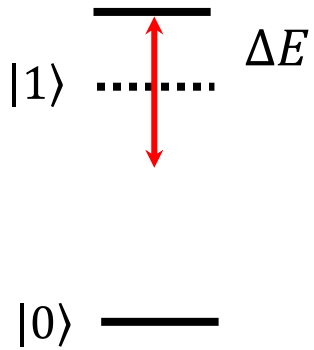
Sensing dynamics (AC) B field



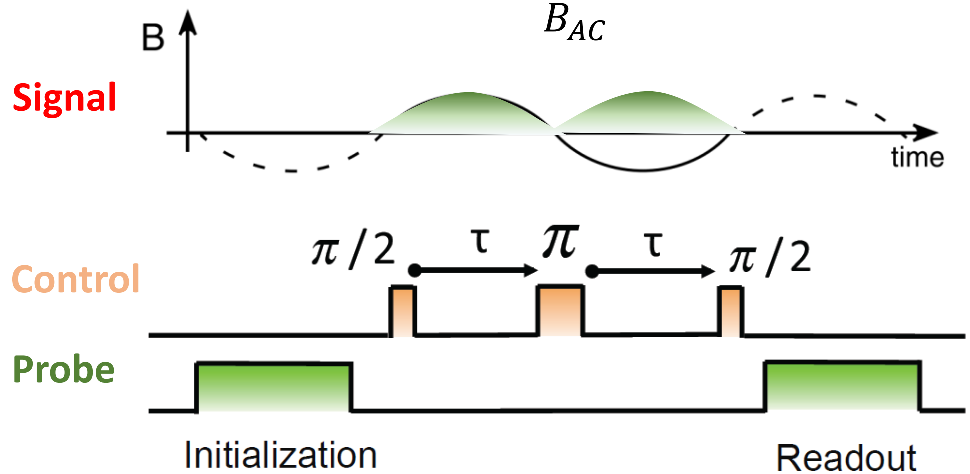
spin Hahn echo

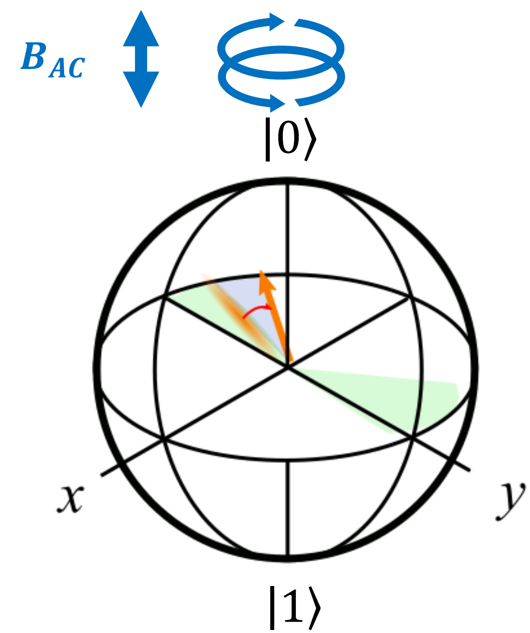


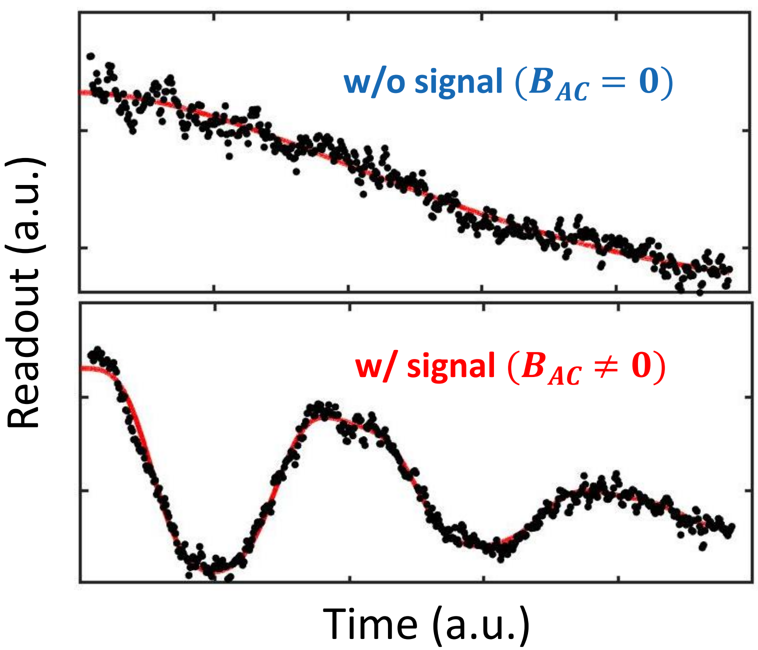
Sensing dynamics (AC) B field



spin Hahn echo

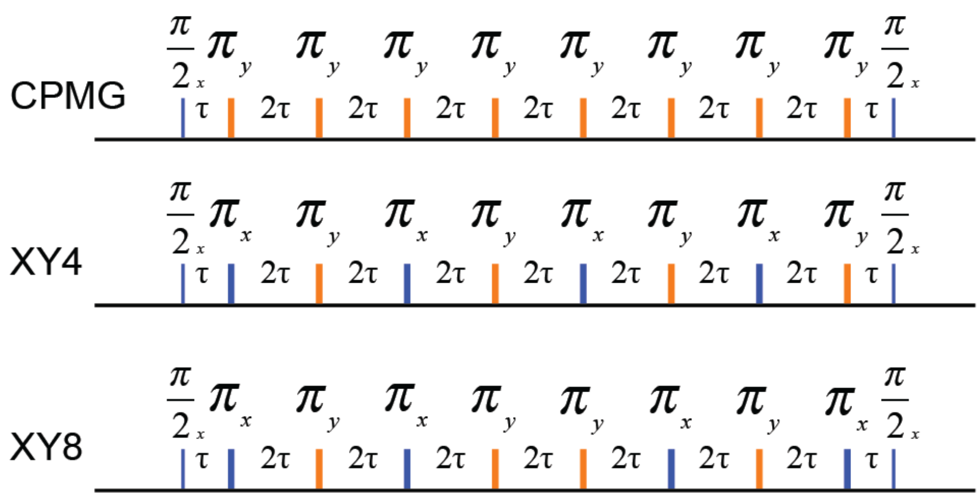


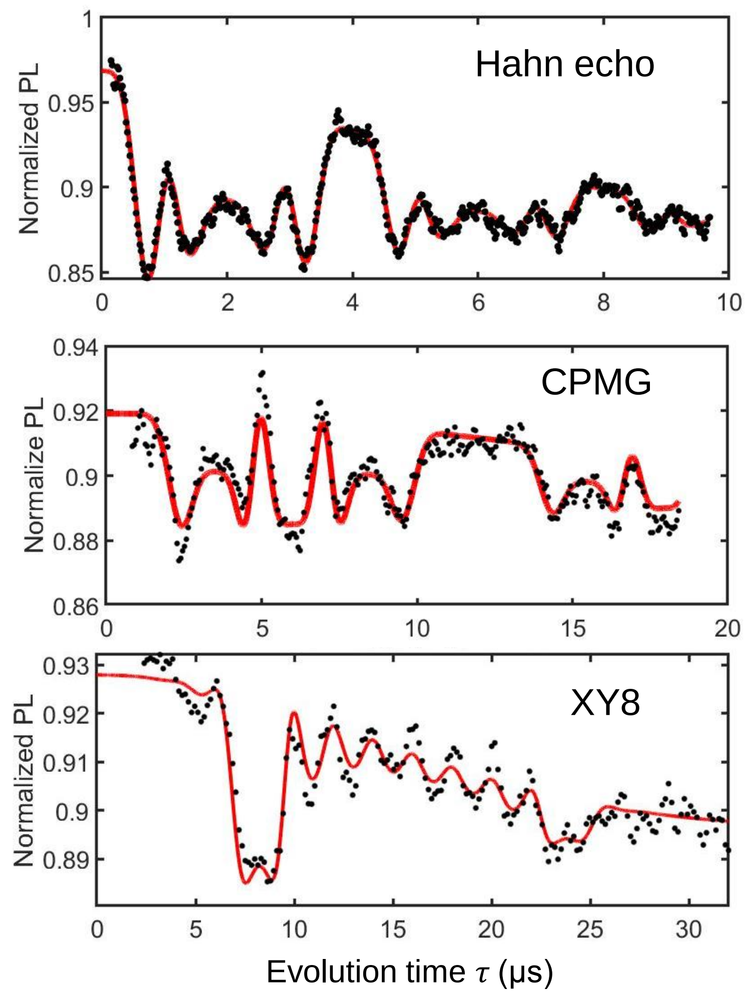




Sensing dynamics (AC) B field

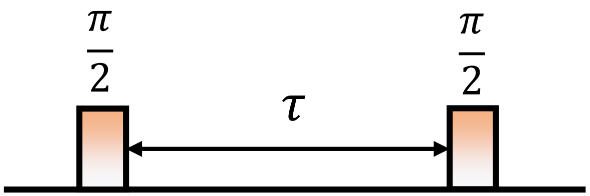
<u>Dynamical decoupling</u>



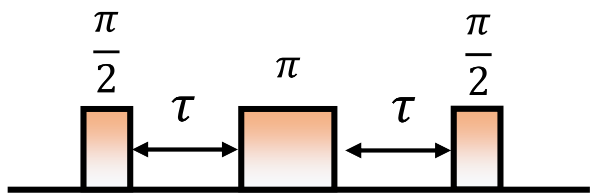


Sensing dynamics (AC) B field

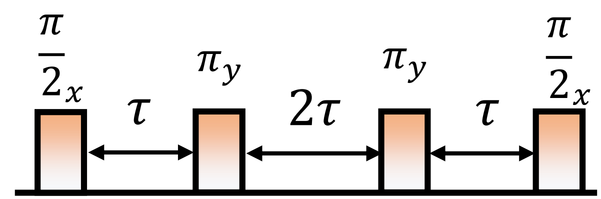
Ramsey



Hahn echo



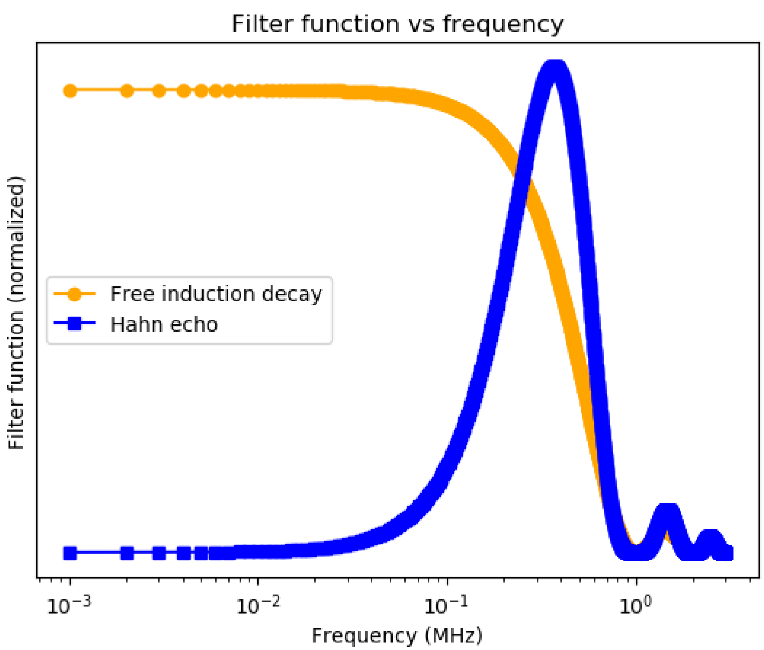
CPMG-N



$$\langle 0|\rho|1\rangle \sim \exp\{-\frac{1}{\hbar^2}\int_{-\infty}^{\infty} d\omega\, \tilde{S}(\omega)\, F(\tau,\omega)\}$$

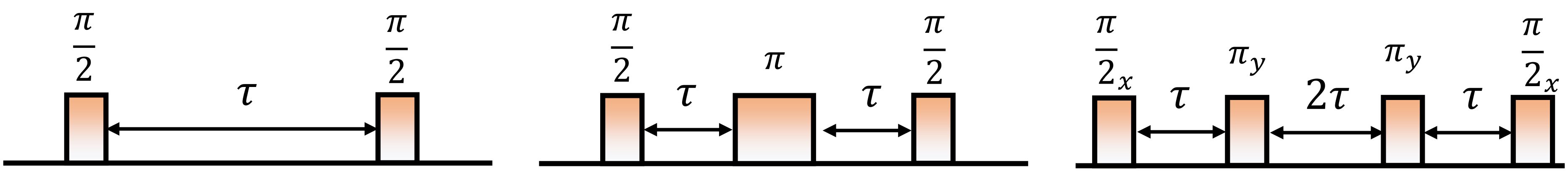
signal

filter function



Sensing dynamics (AC) B field

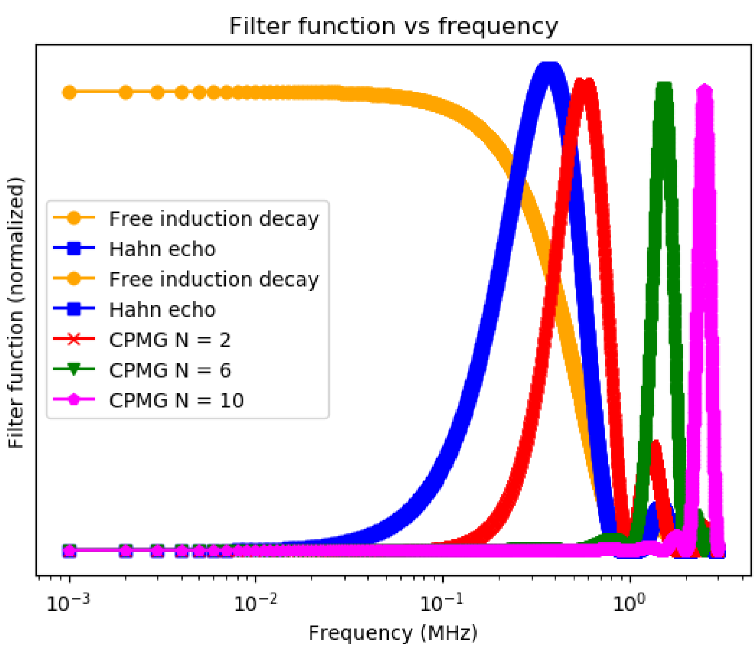
Ramsey | Hahn echo | CPMG-N

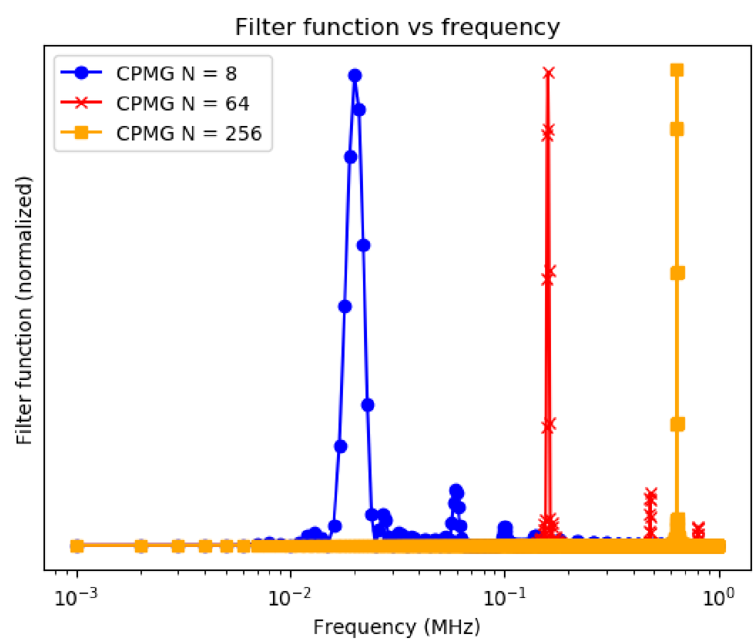


$$\langle 0|\rho|1\rangle \sim \exp\{-\frac{1}{\hbar^2}\int_{-\infty}^{\infty} d\omega \tilde{S}(\omega)\, F(\tau,\omega)\}$$

signal

filter function

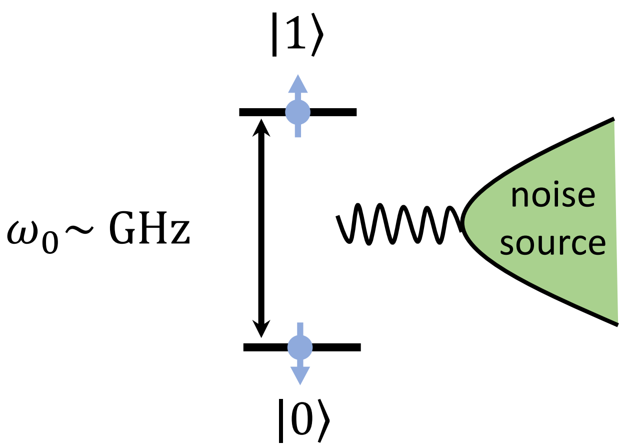


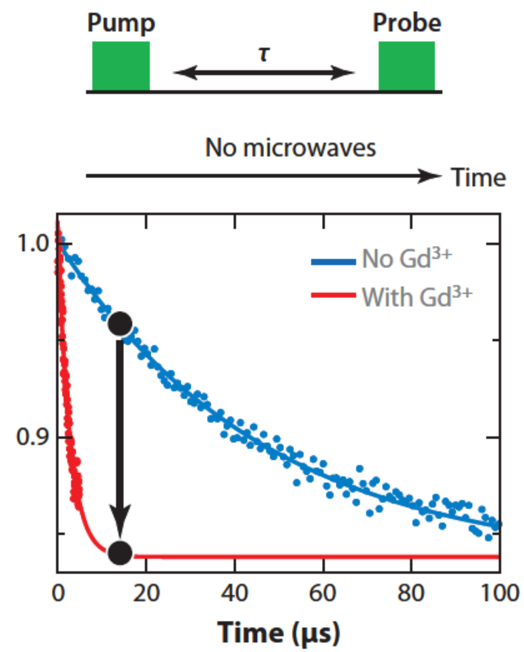


Sensing dynamics (AC) B field

General quantum sensing methods

- DC (dc ~ kHz) : Ramsey
- AC (kHz ~ 100 kHz) : Echo
- AC (~ MHz) : CPMG, XY4, XY8
- ⋮
- AC (~ GHz) : T_1 relaxometry

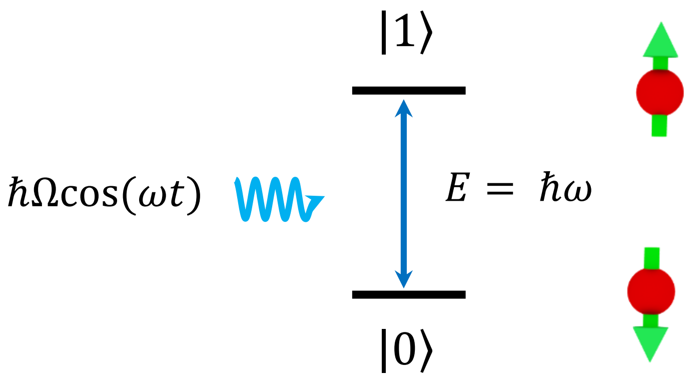


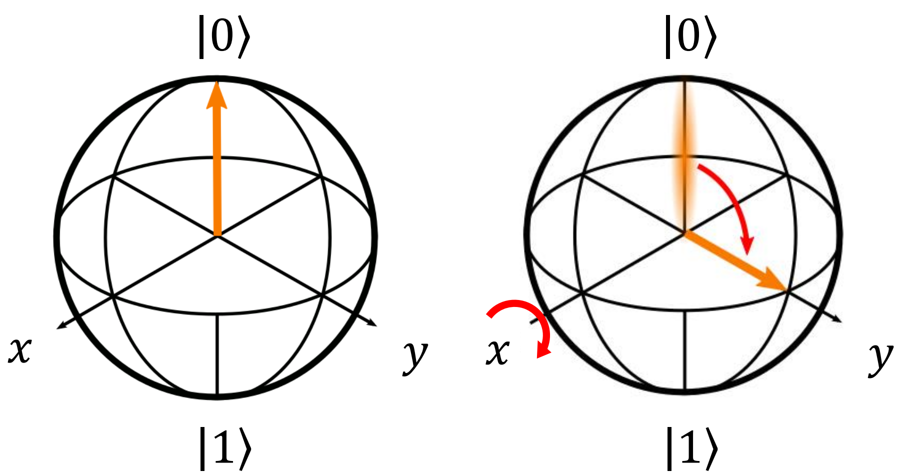


R. Schirhagl *et al.*, Annu. Rev. Phys. Chem. (2014)

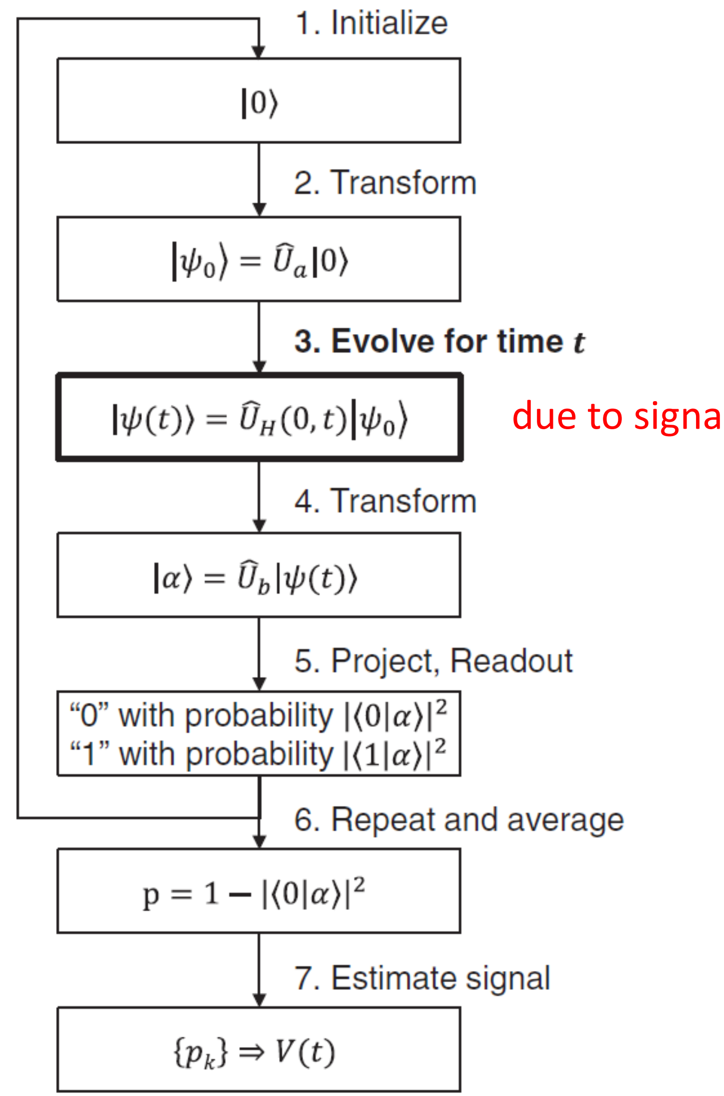
Quantum sensing protocol

Qubit



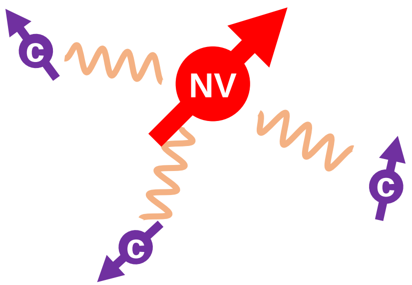


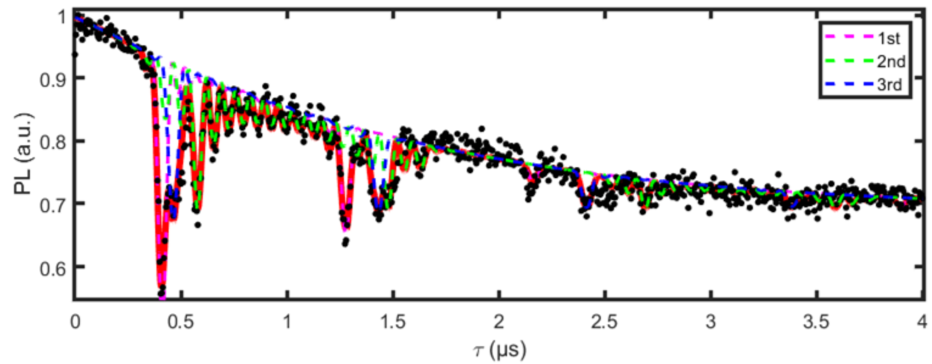
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



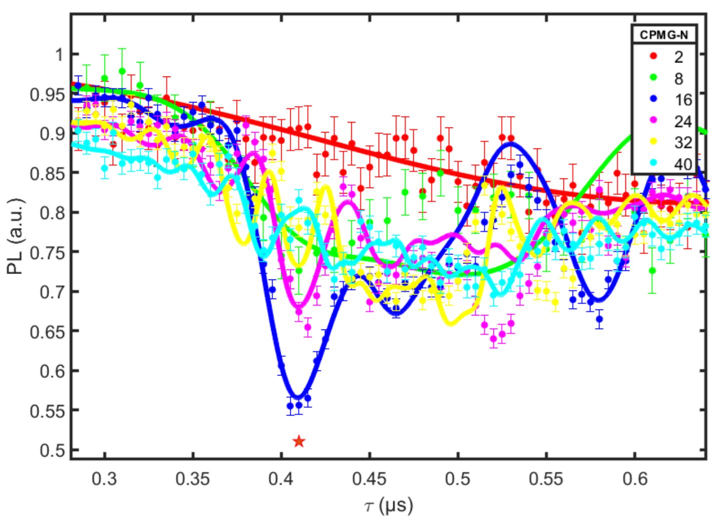
C. L. Degen *et al.*, Rev. of Mod. Phys. (2017)

Advanced quantum sensing with multi-qubits

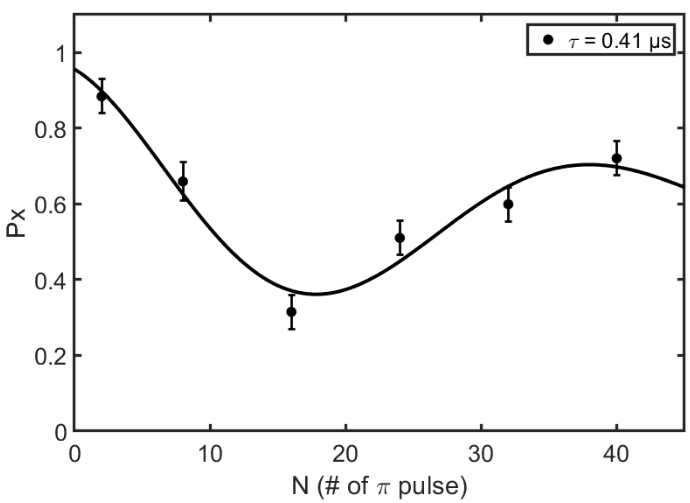




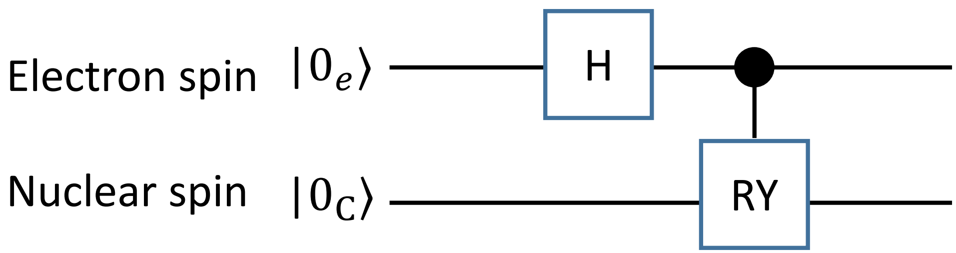
^{13}C index	1	2	3
$A_{\|\|}$ (kHz)	167.7 $\pm$ 11.2	- 46.2 $\pm$ 11.8	54.6 $\pm$ 12.0
$A_{\perp}$ (kHz)	99.65 $\pm$ 6.9	148.8 $\pm$ 2.4	55.1 $\pm$ 2.9



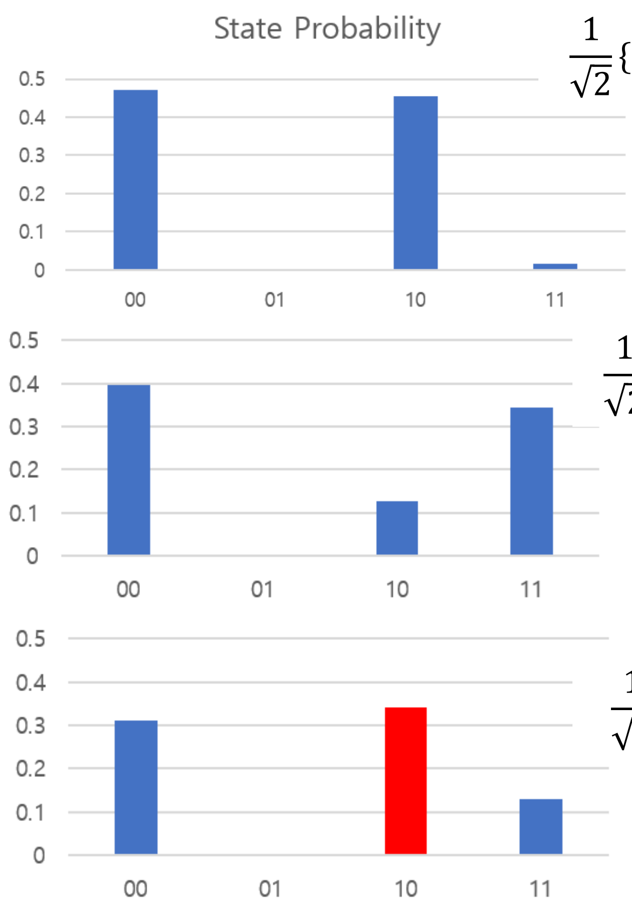
CPMG based $\mathrm{C_eNOT_n}$ operation



Advanced quantum sensing with multi-qubits



$$\frac{1}{\sqrt{2}}\{|0_e0_C\rangle + |1_e\rangle \otimes (\cos\left(\frac{\phi}{2}\right)|0_C\rangle + \sin(\frac{\phi}{2})|1_C\rangle)\}$$

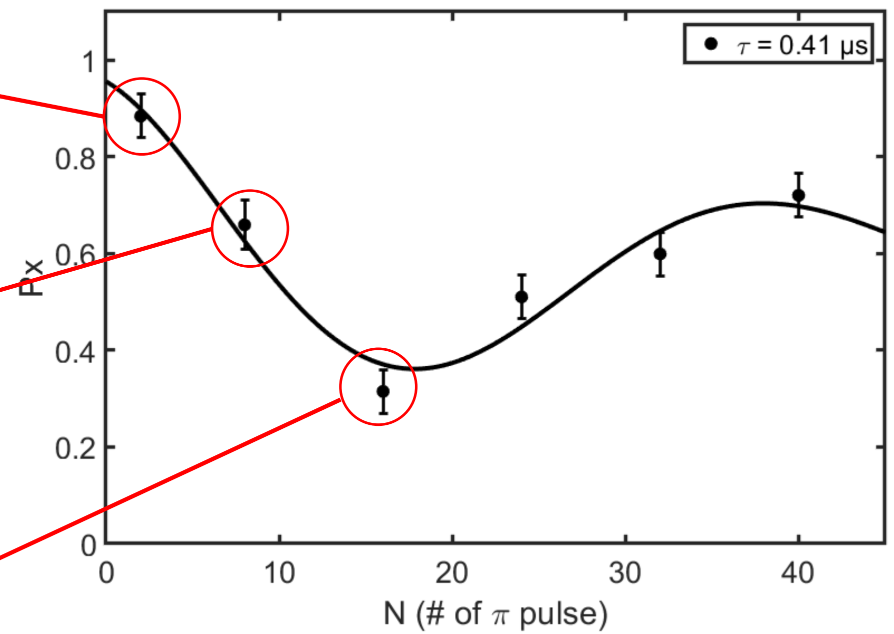


$$\frac{1}{\sqrt{2}}\{|0_e0_C\rangle + |1_e0_C\rangle\}$$

$$\frac{1}{\sqrt{2}}\{|0_e0_C\rangle + |1_e1_C\rangle\}$$

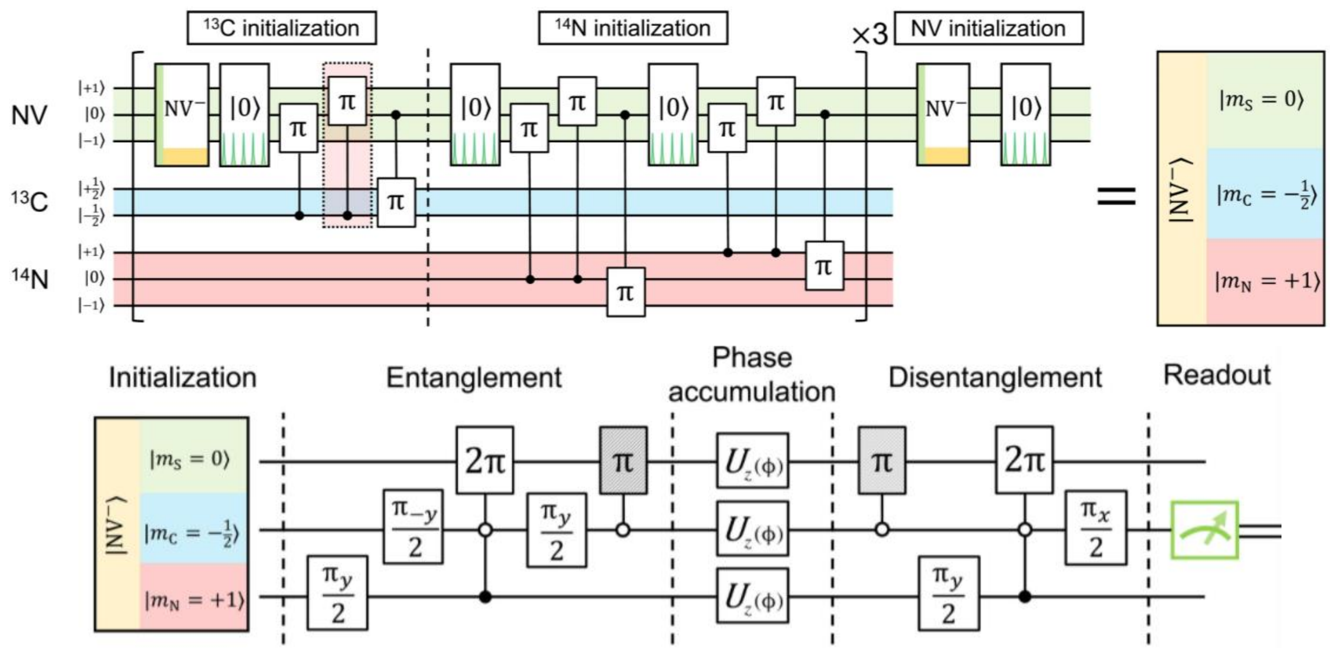
Bell state

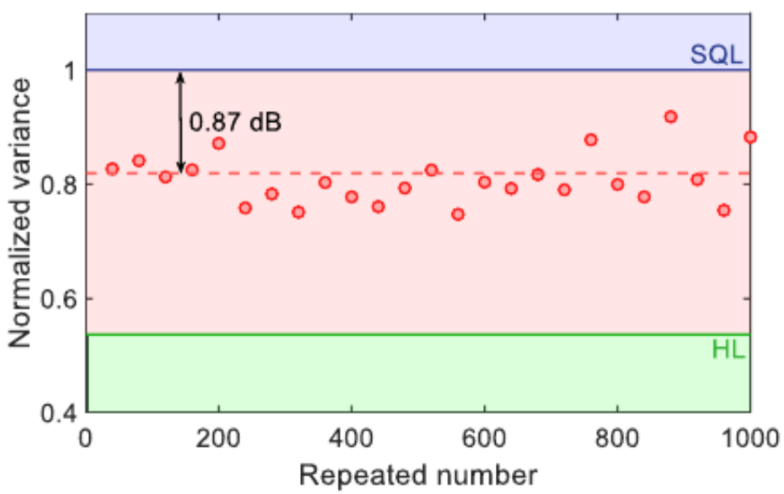
$$\frac{1}{\sqrt{2}}\{|0_e0_C\rangle - |1_e0_C\rangle\}$$



Advanced quantum sensing with multi-qubits

Quantum sensing below standard quantum limit

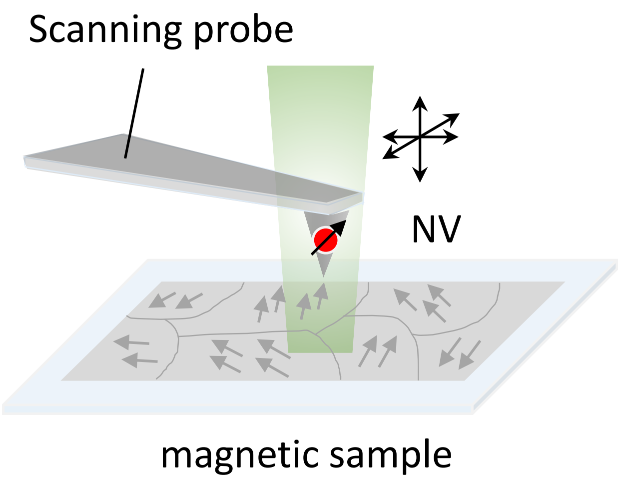




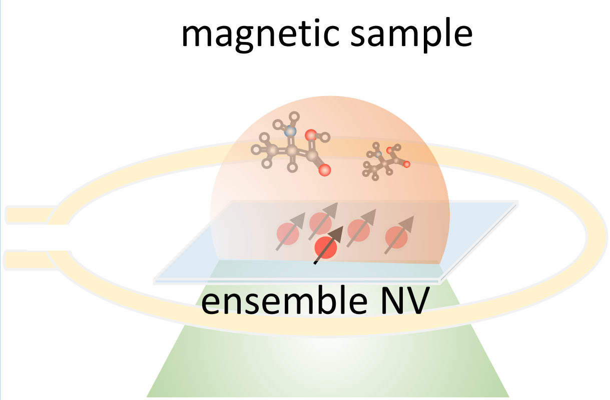
T. Xie et al. Science Advances (2021)

Quantum imaging based on diamond NV centers

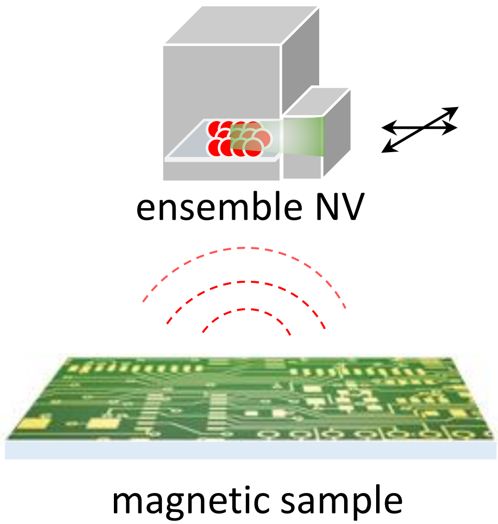
nm scale imaging



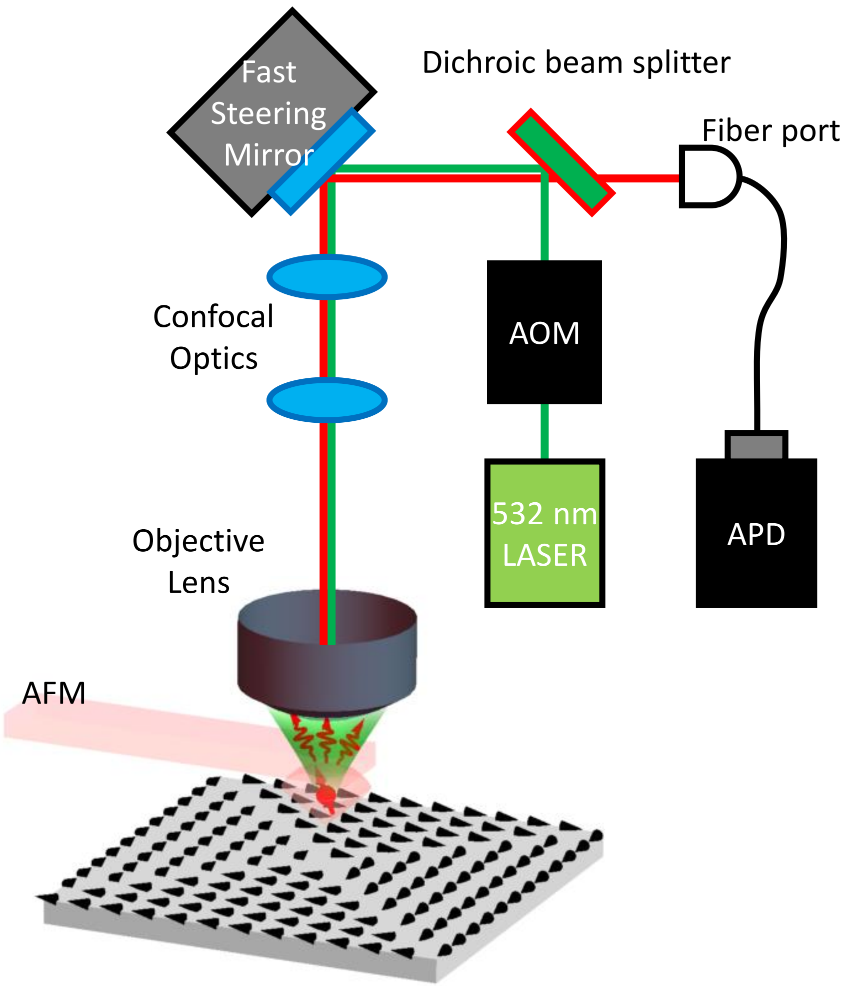
μm scale imaging

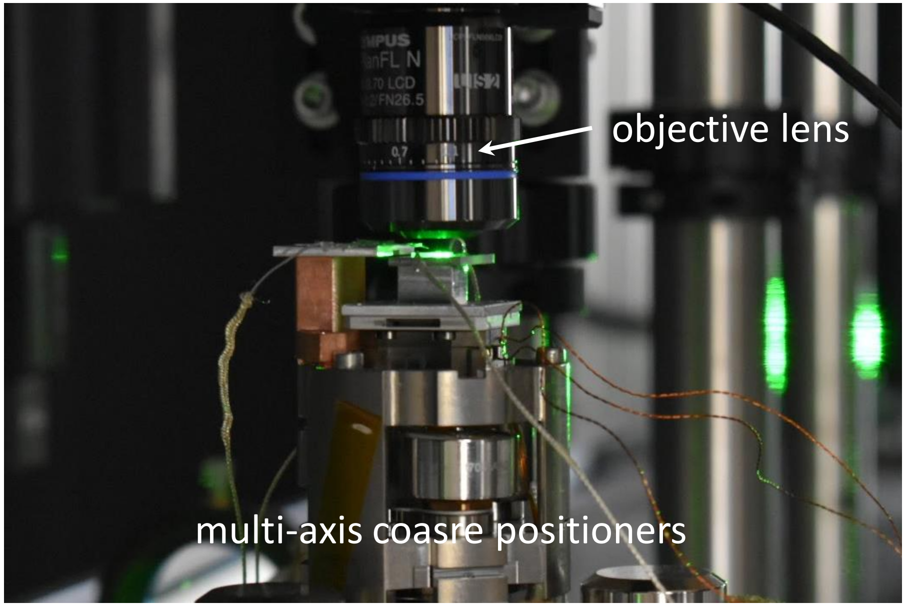


mm scale imaging

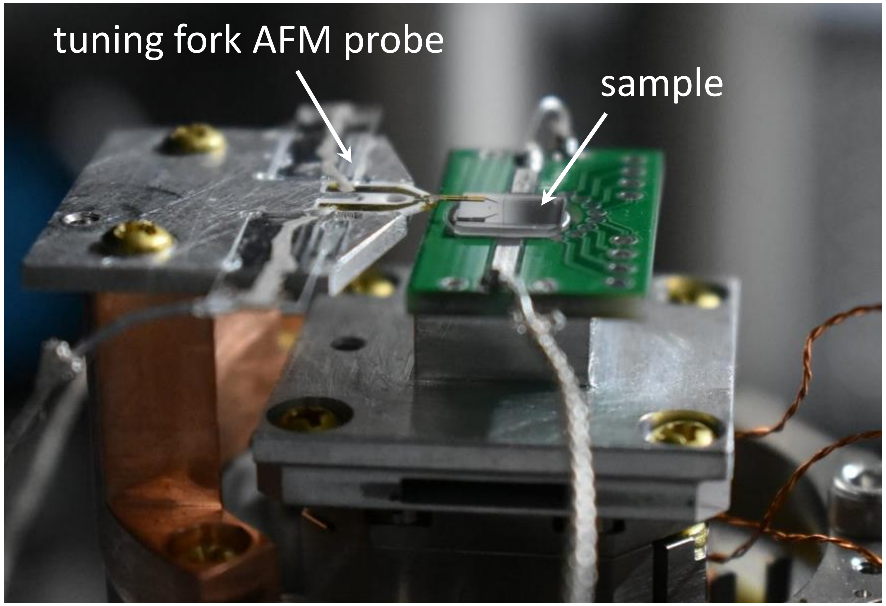


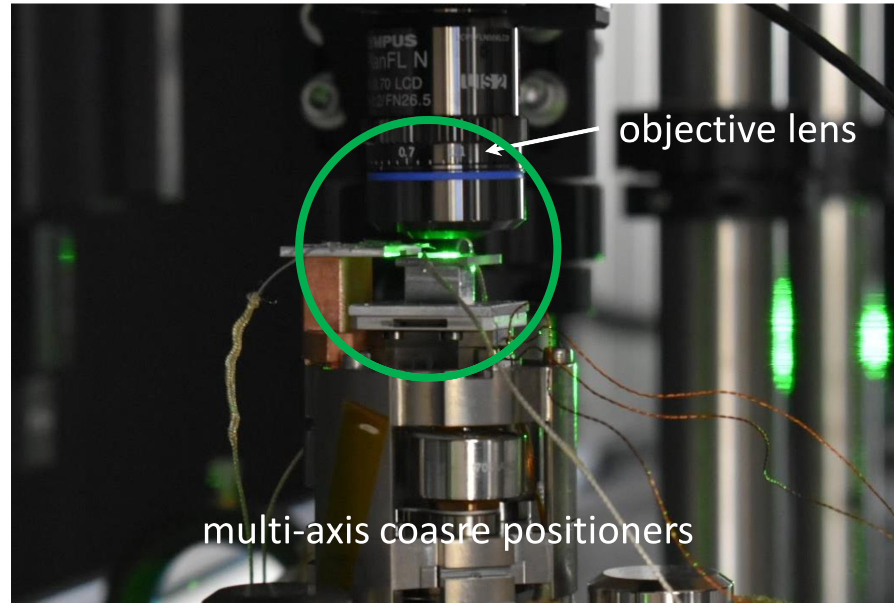
Imaging with single spin scanning magnetometer



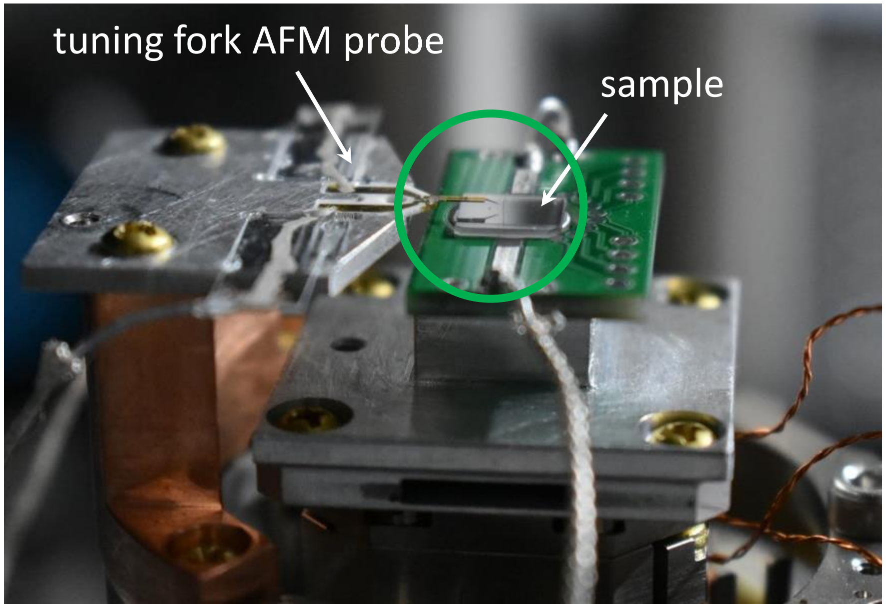


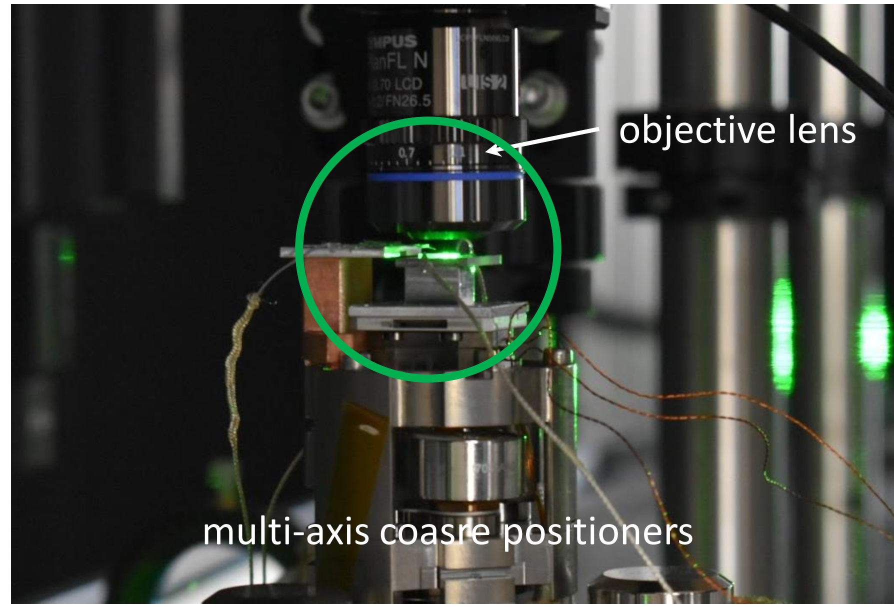
Imaging with single spin scanning magnetometer

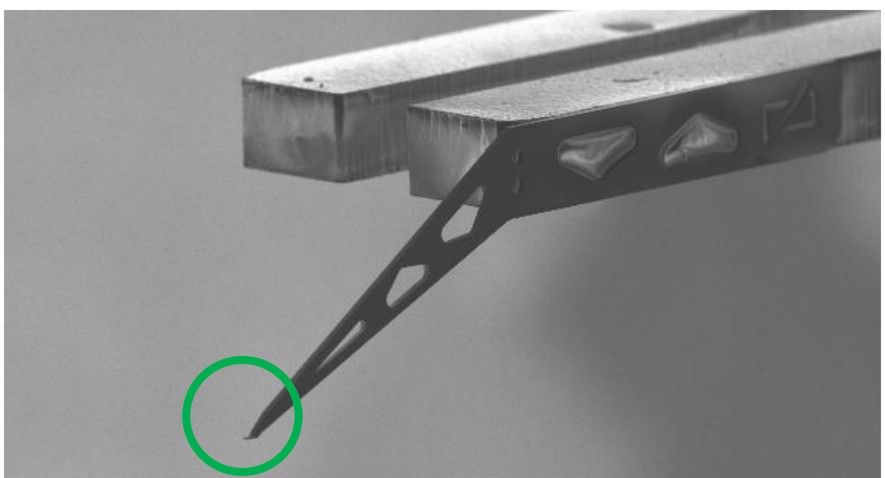




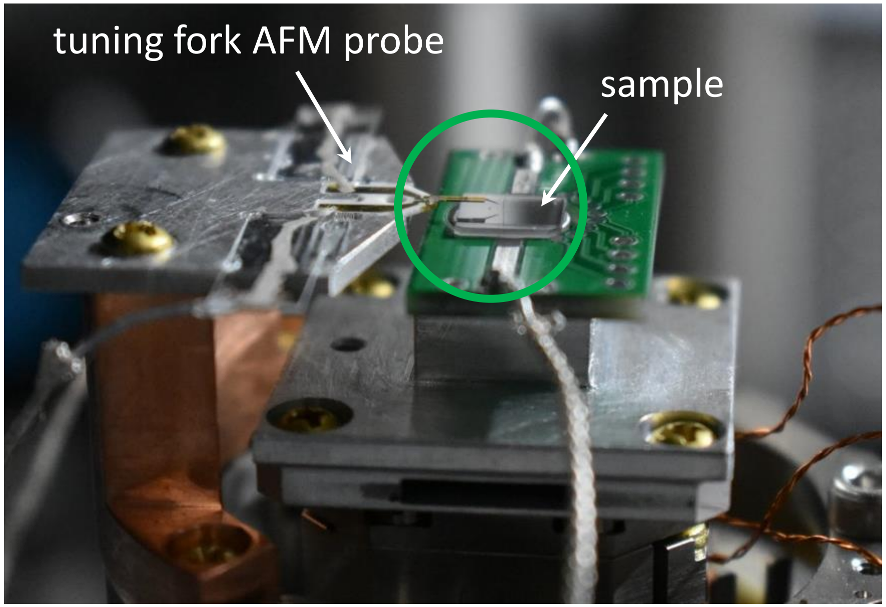
Imaging with single spin scanning magnetometer

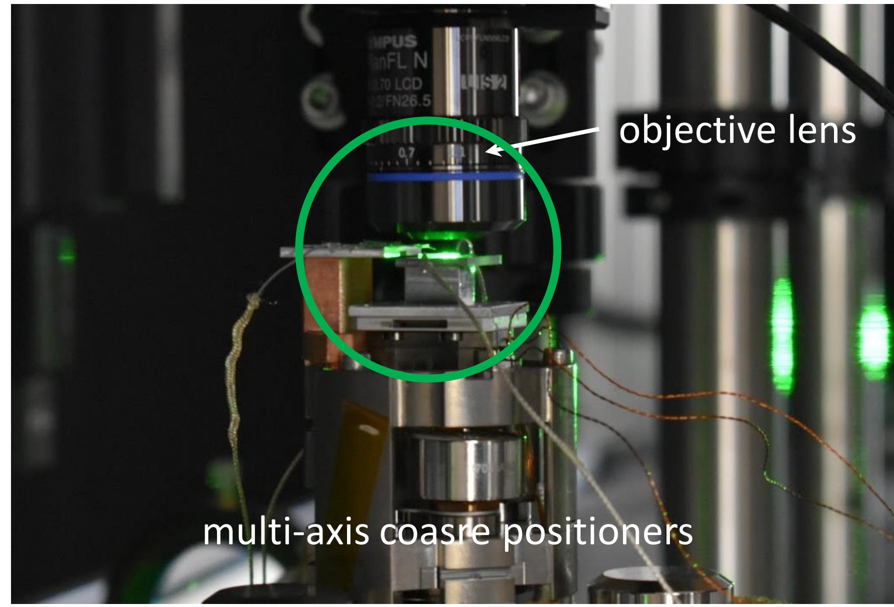


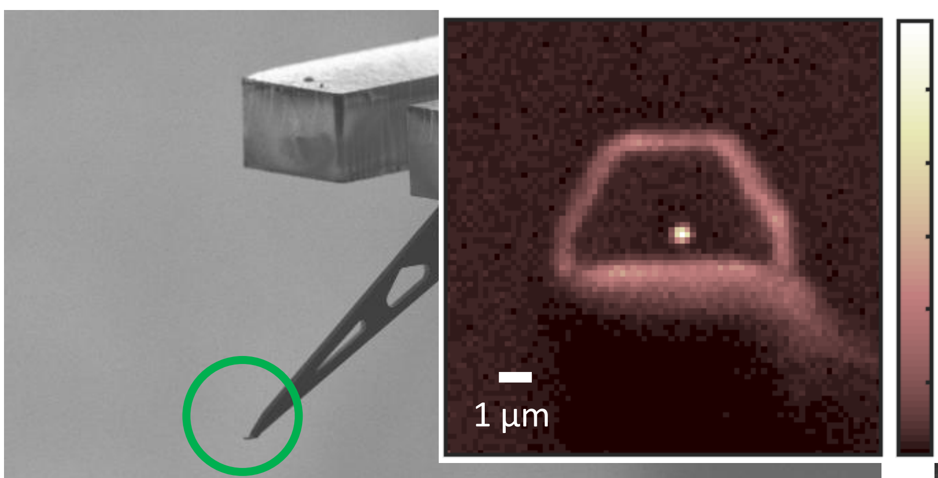


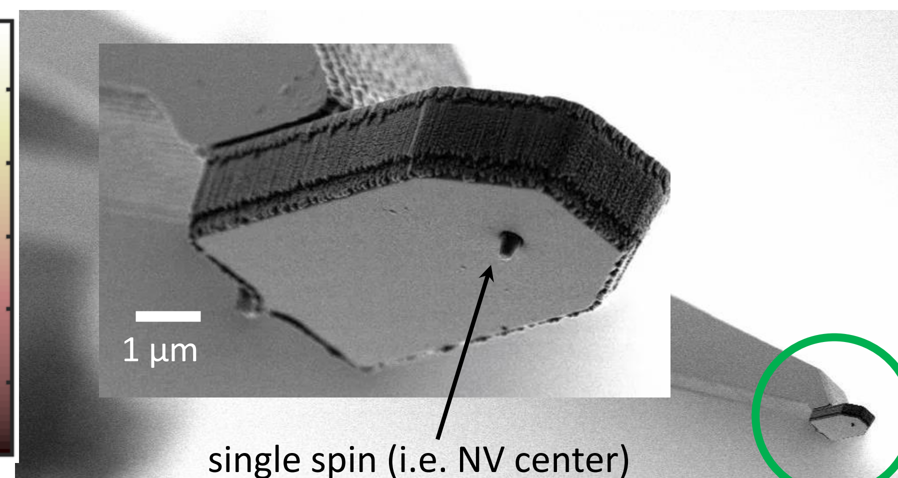


Imaging with single spin scanning magnetometer





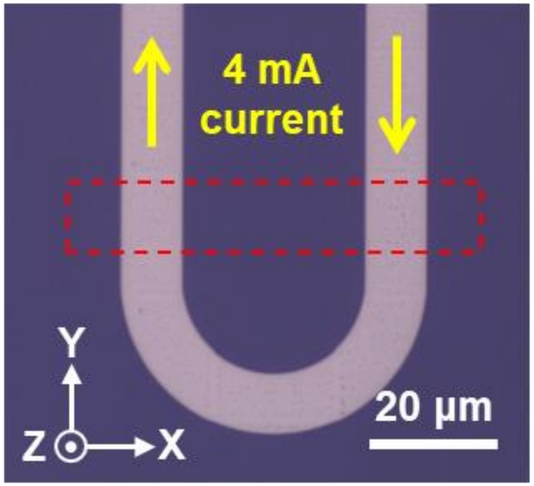




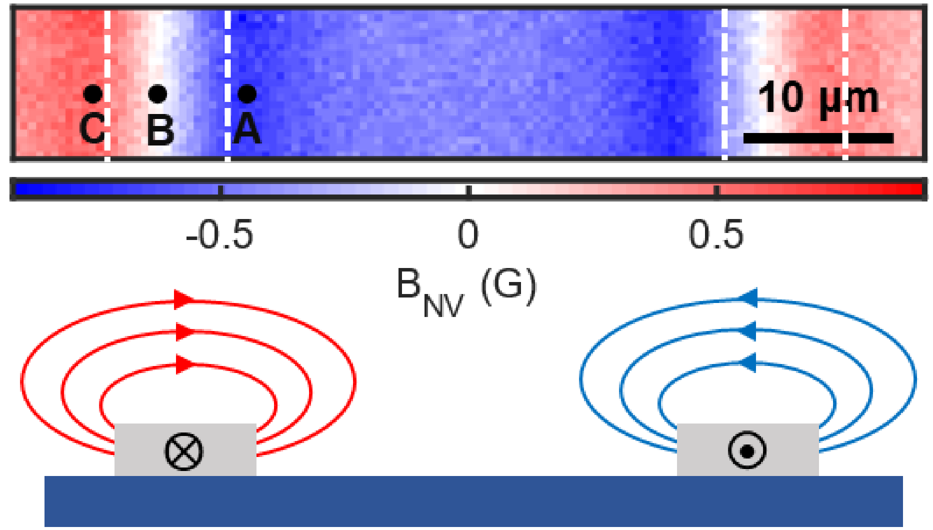
at the tip apex

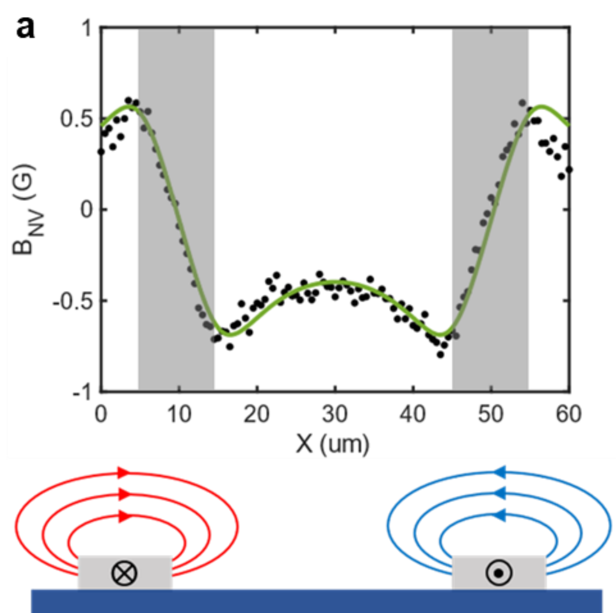
Imaging example with current device

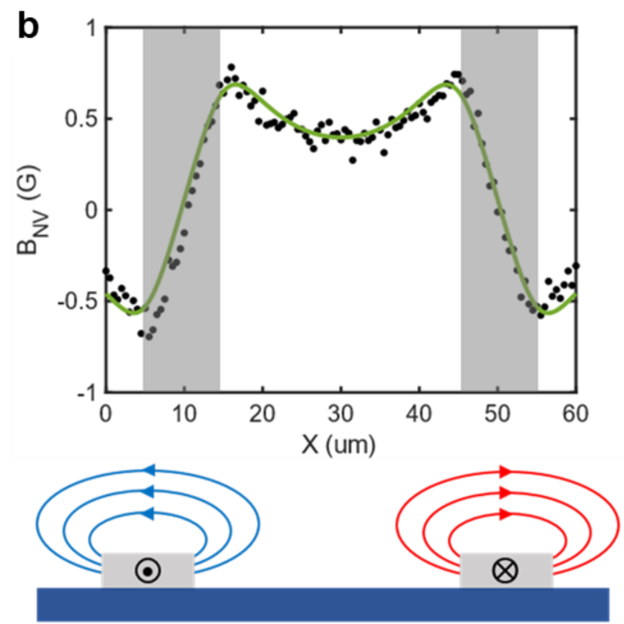
- Optical image of Pt wire



- Magnetic field image of the dashed area

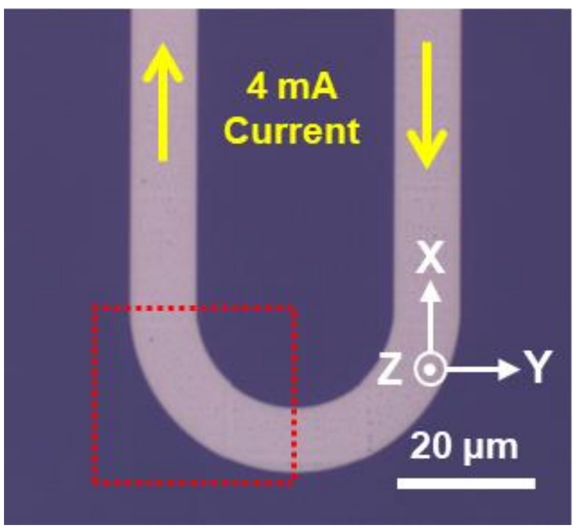


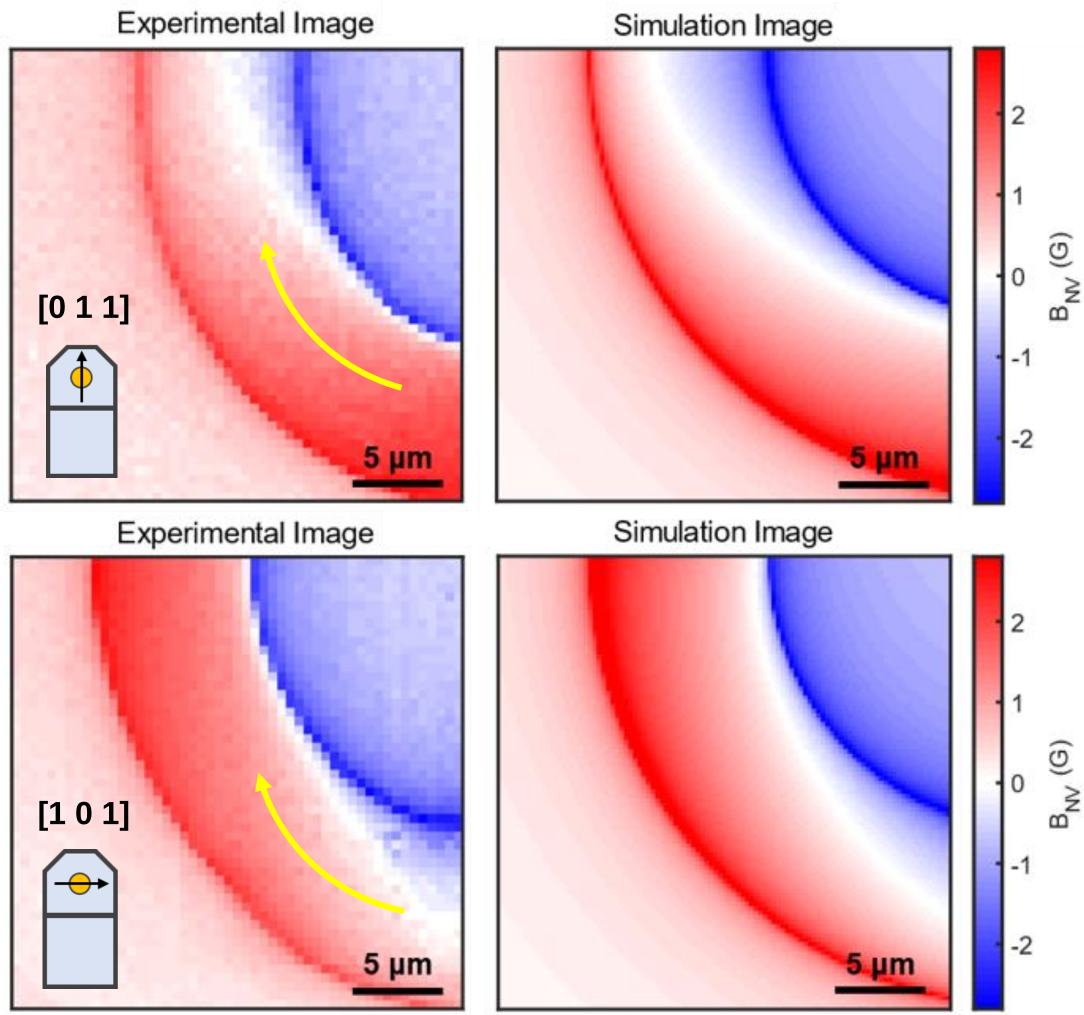




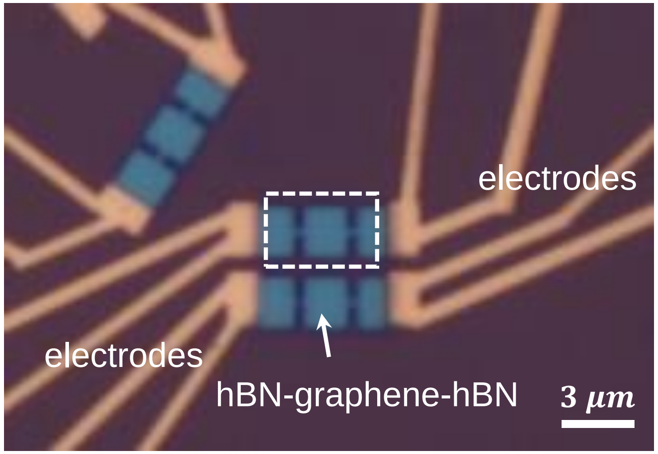
Imaging example with current device

- Optical image of Pt wire

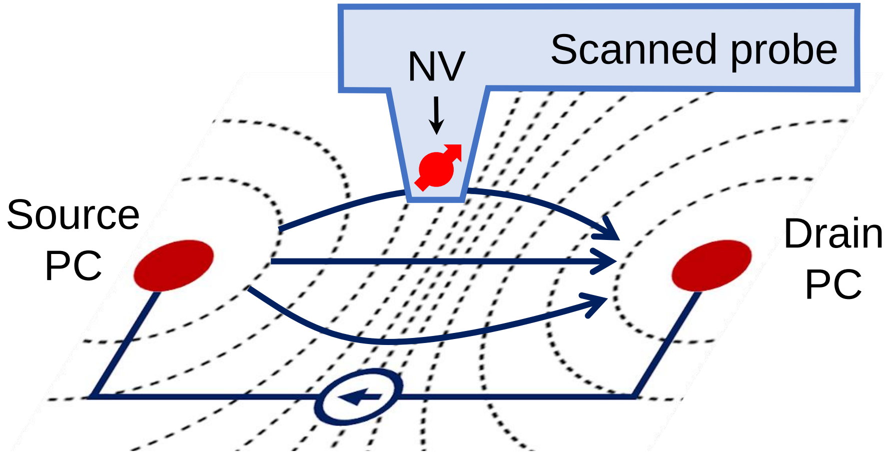


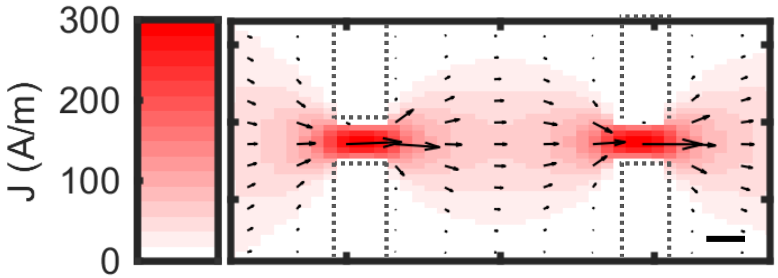


Imaging example with graphene device

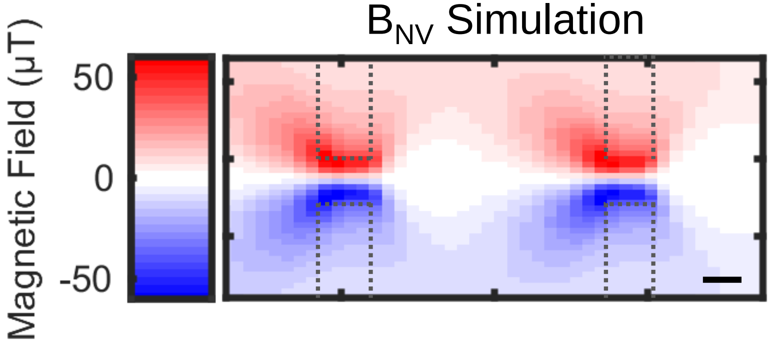


Graphene sample (Prof. Gil-Ho Lee, POSTECH)



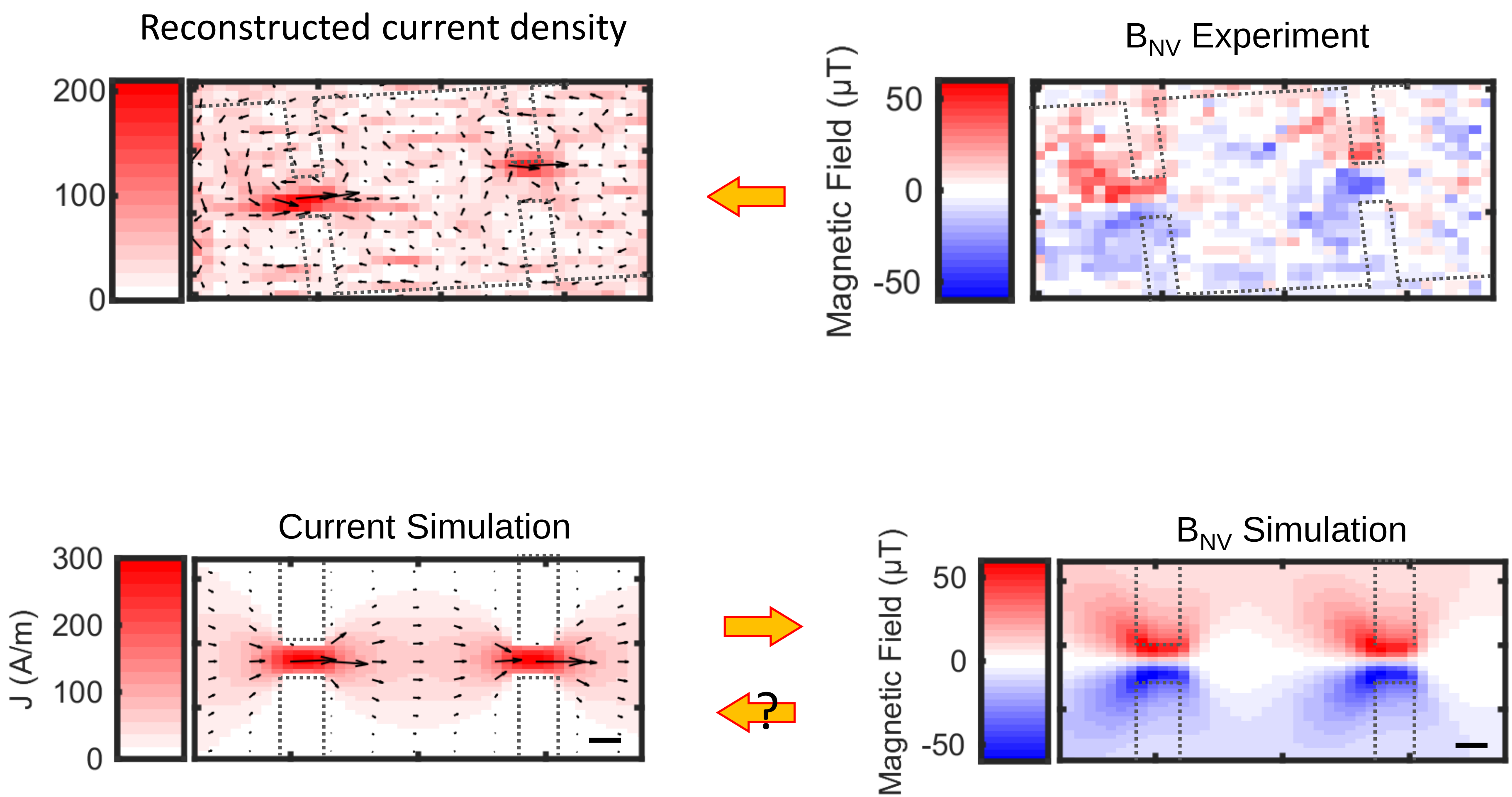


?



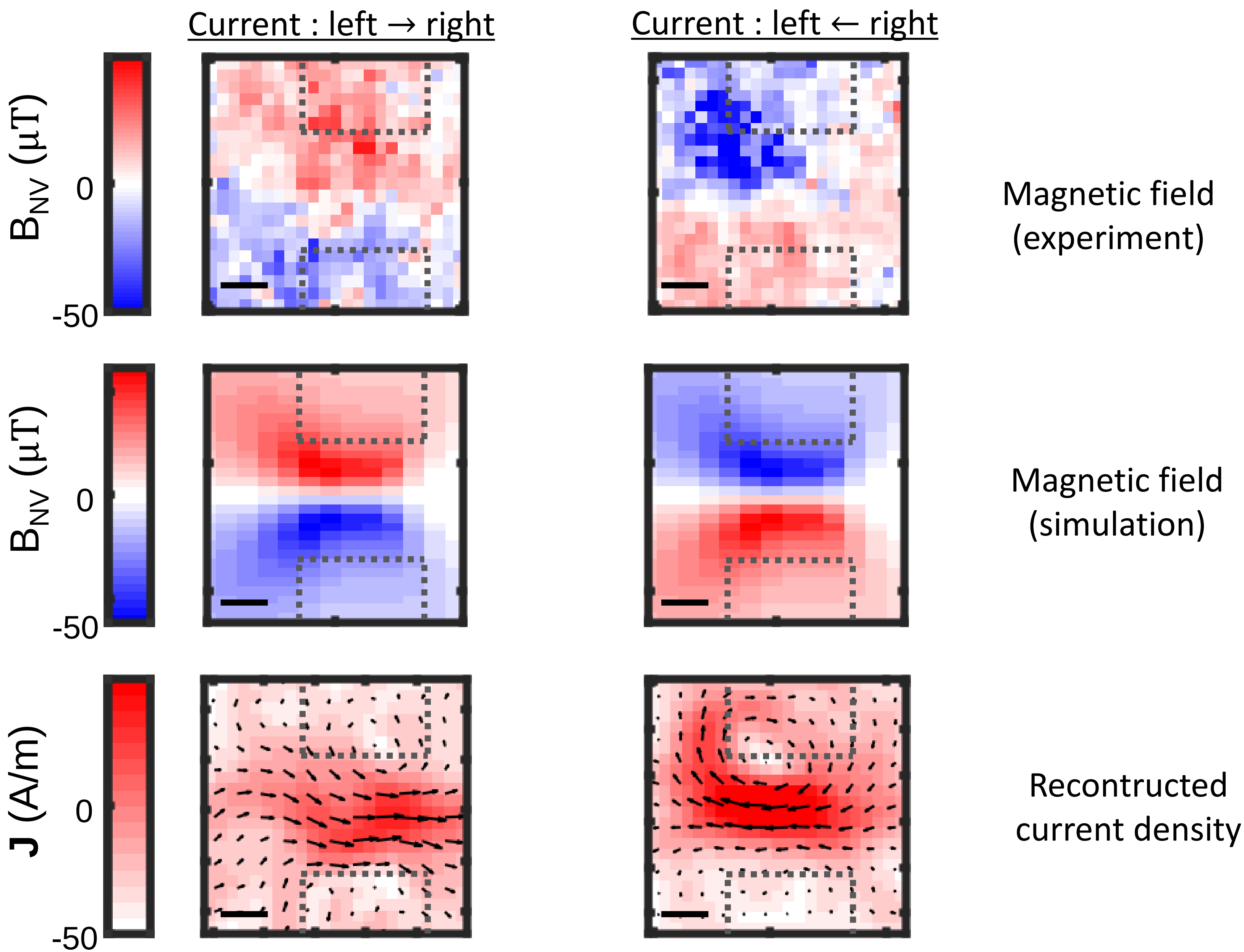
Is a single component of magnetic field enough to reconstruct current profile ?   Yes!

Imaging example with graphene device



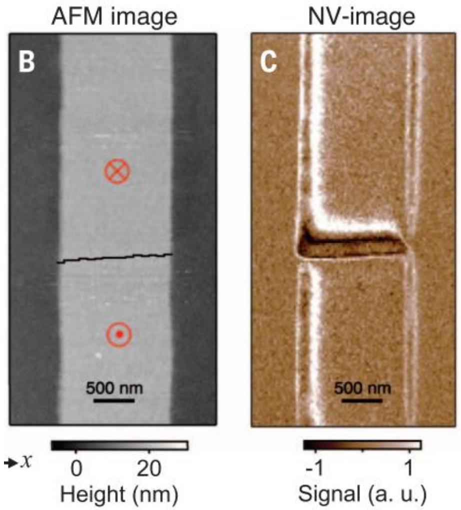
Is a single component of magnetic field enough to reconstruct current profile ? Yes!

Imaging example with graphene device



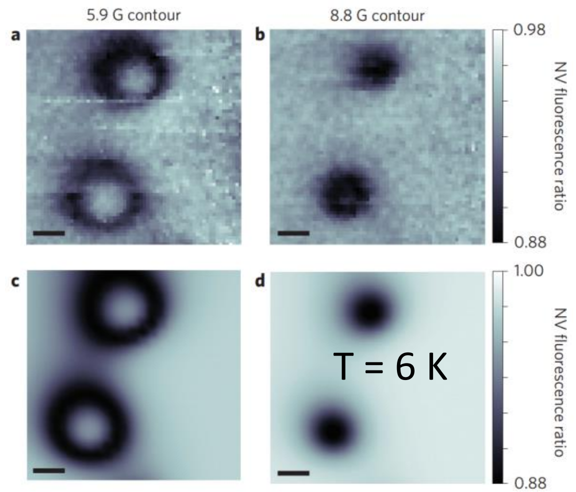
More imaging examples

Domain wall



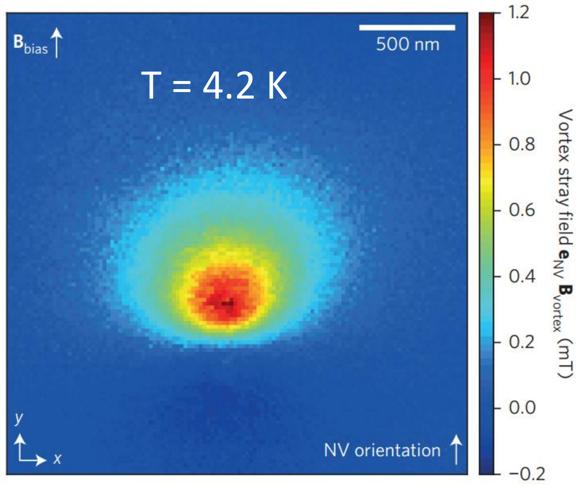
J. P. Tetienne *et al.*, Science (2014)

Superconducting vortices in $BaFe_2(As_{0.7}P_{0.3})_2$



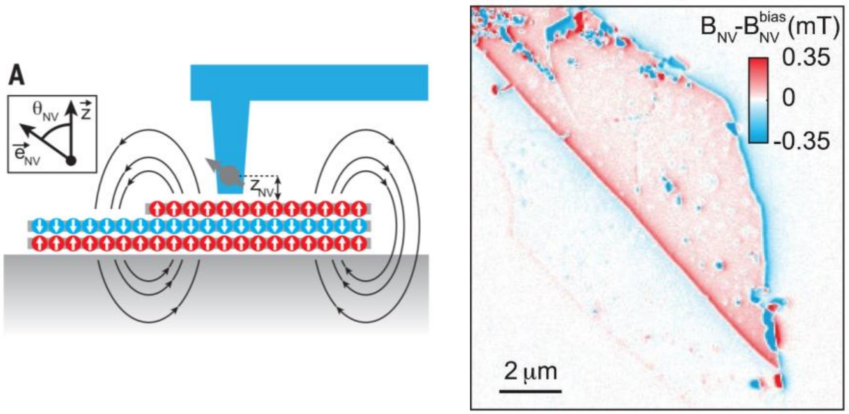
M. Pelliccione *et al.*, Nat. Nano. (2016)

Superconducting vortex in YBCO



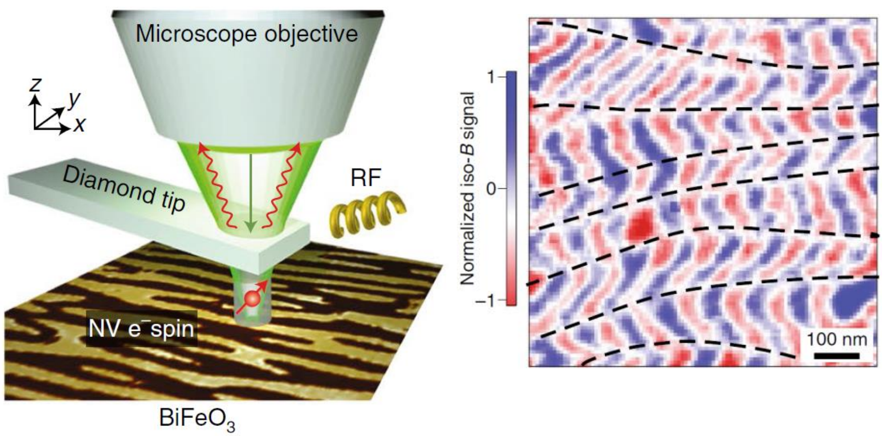
L. Thiel *et al.*, Nat. Nano. (2016)

2D ferromagnetism



L. Thiel et al., Science (2019)

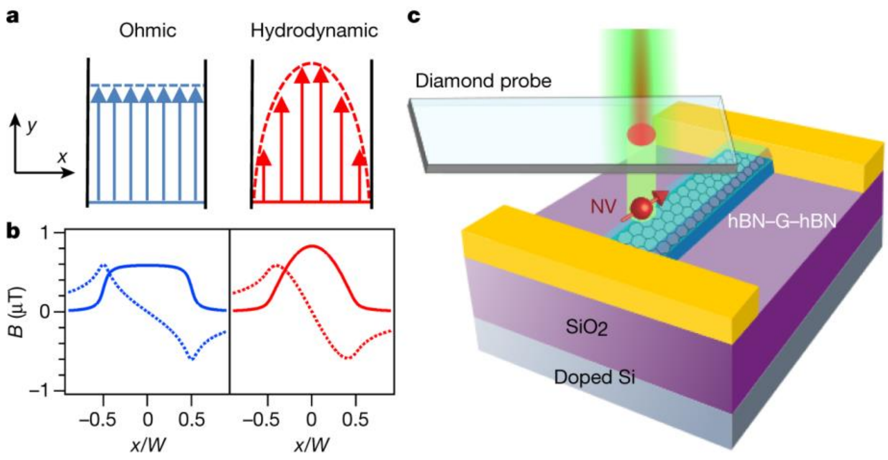
Anti-ferromagnetic order

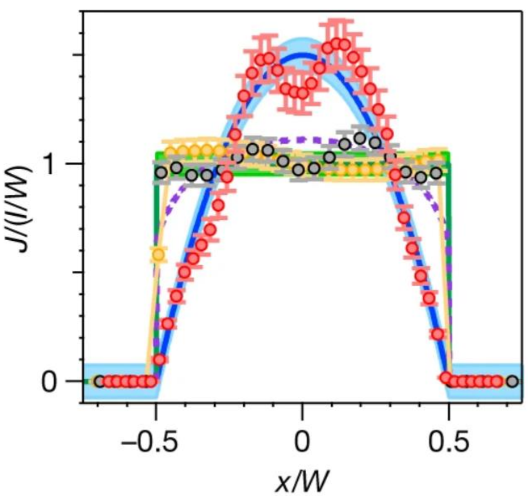


I. Gross et al. Nature (2017)

More imaging examples

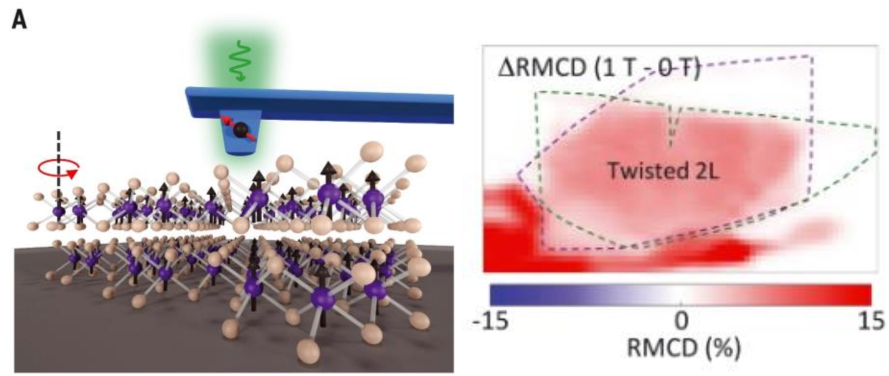
Imaging viscous flow in graphene

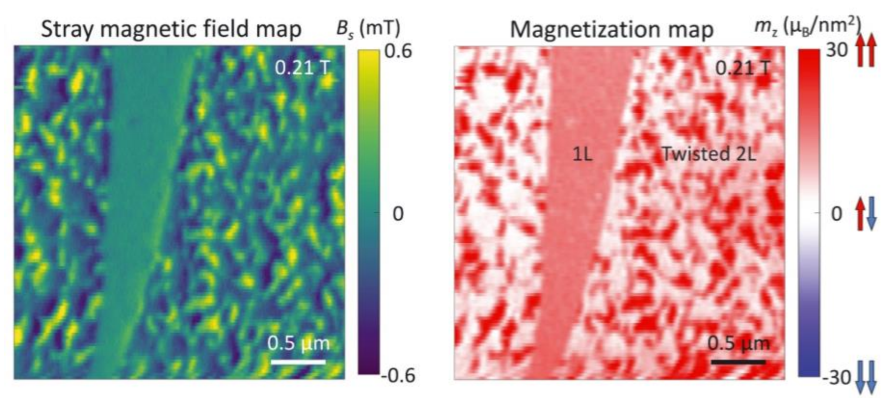




M. J. H. Ku et al. Nature (2020)

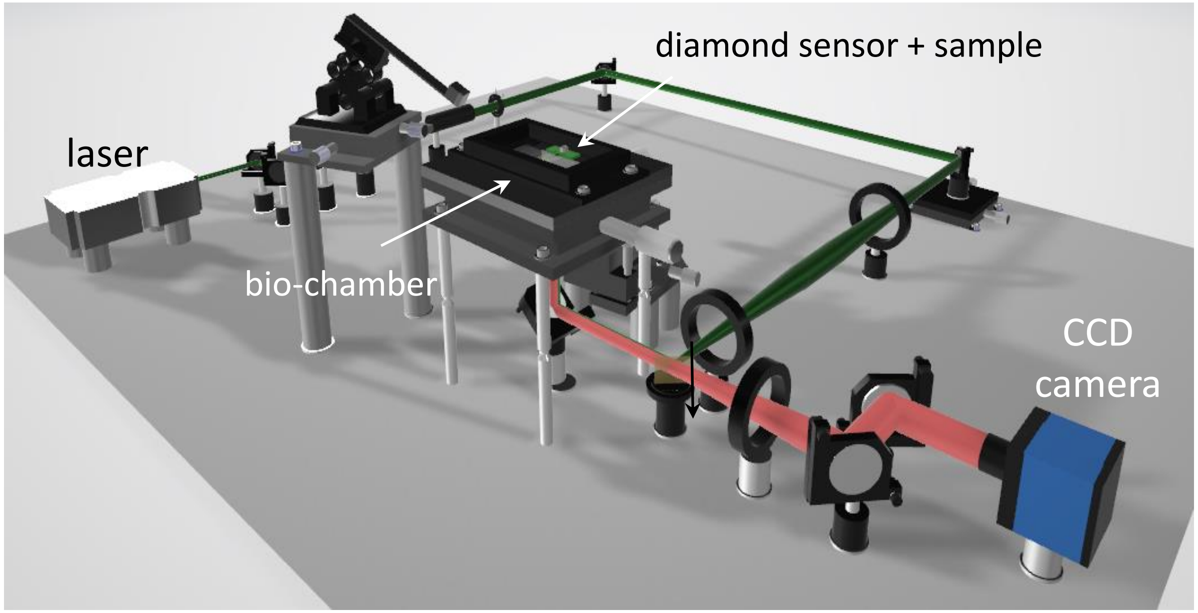
Imaging magnetic domains in twisted CrI_3

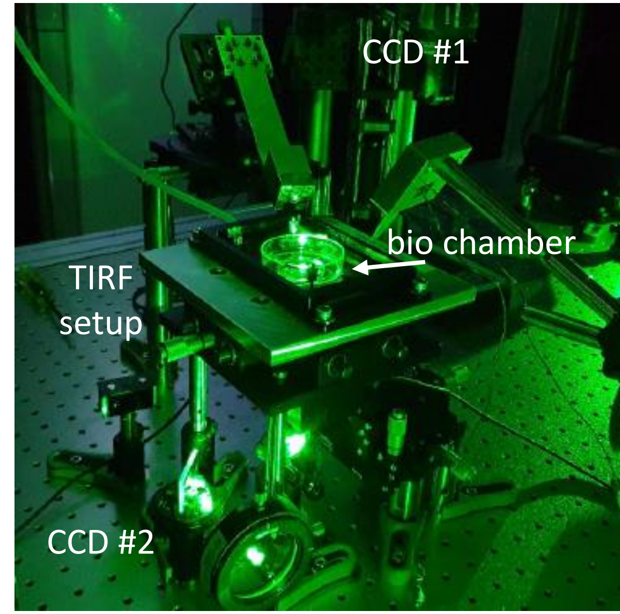


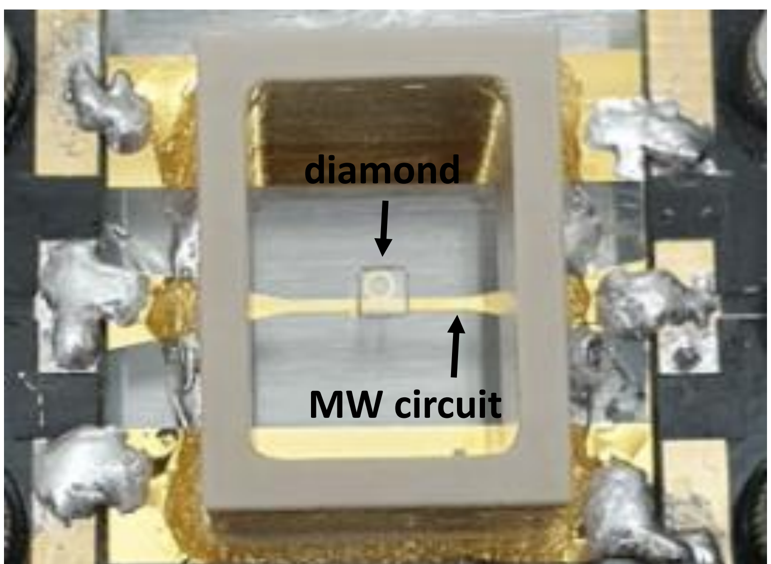


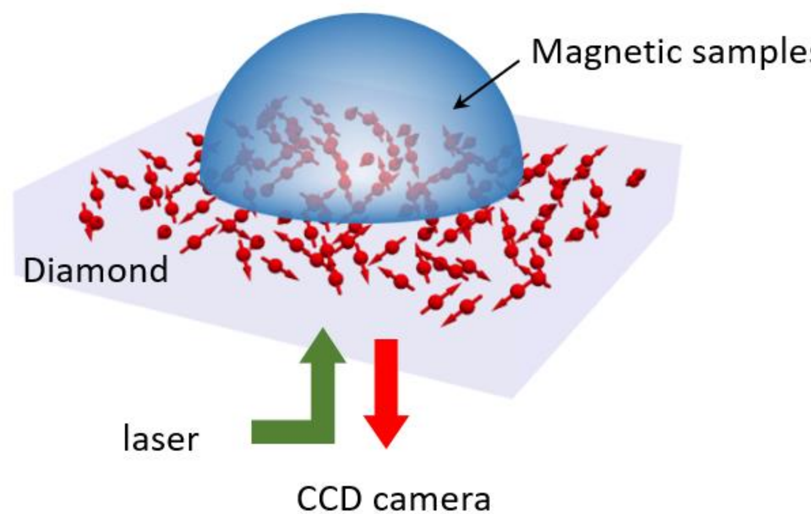
T. Song et al. Science (2021)

Imaging with wide-field quantum microscope

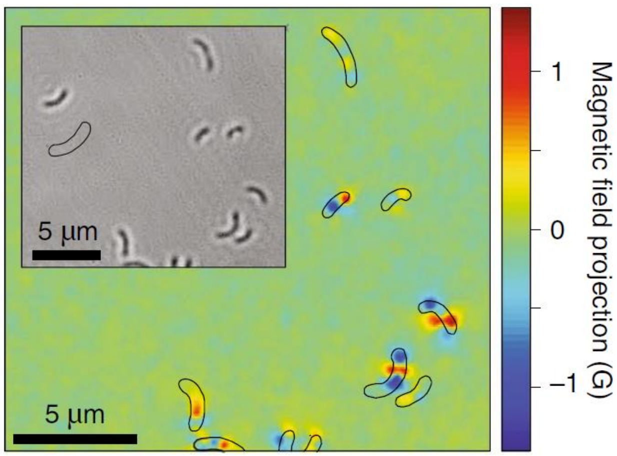




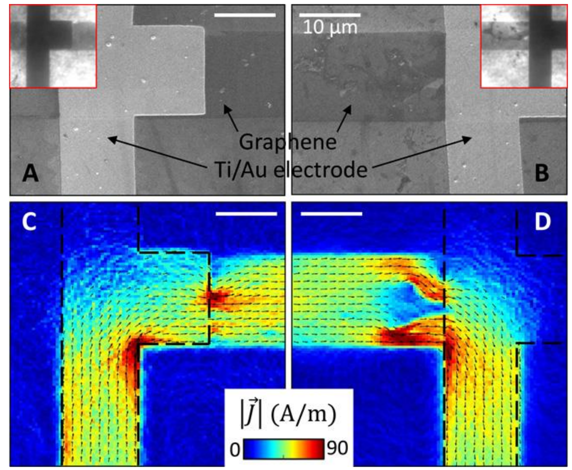




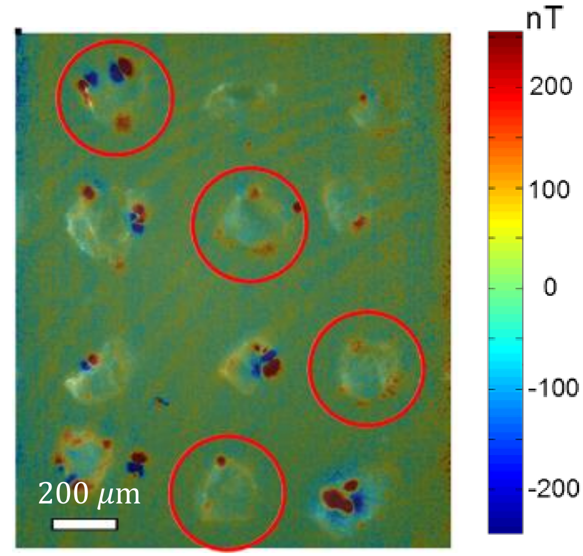
More imaging examples



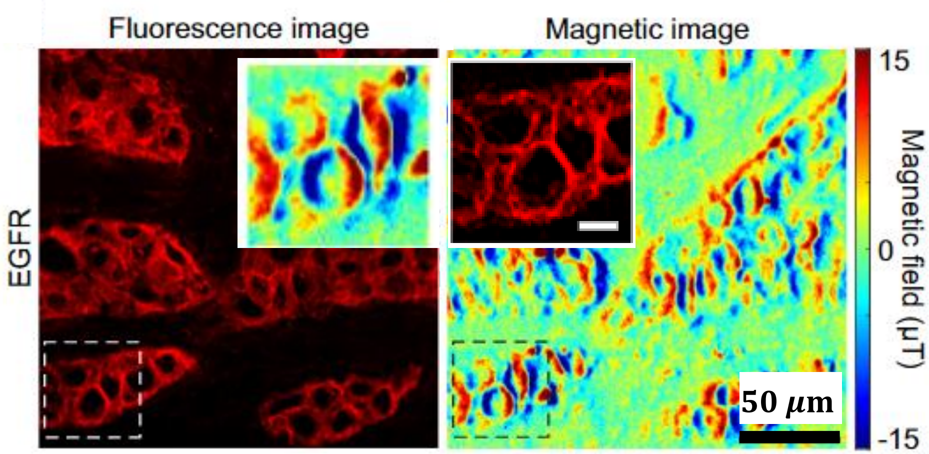
Le Sage et al. Nature (2013)



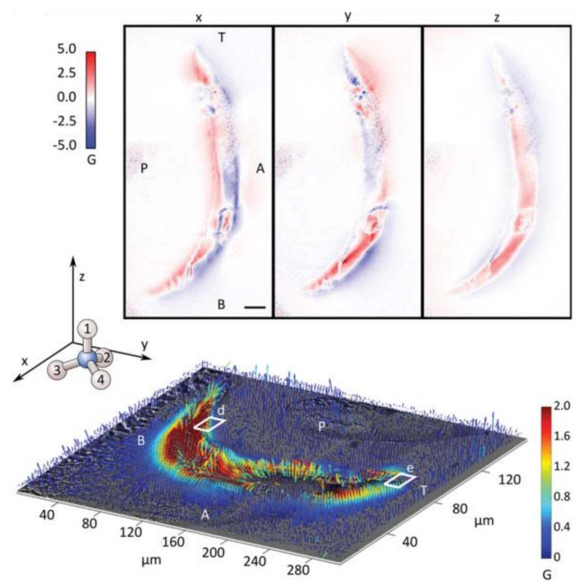
J-T Tetienne et al. Science Advacnes (2017)



Glenn et. al. Geo. Geophys. Geosys. (2017)



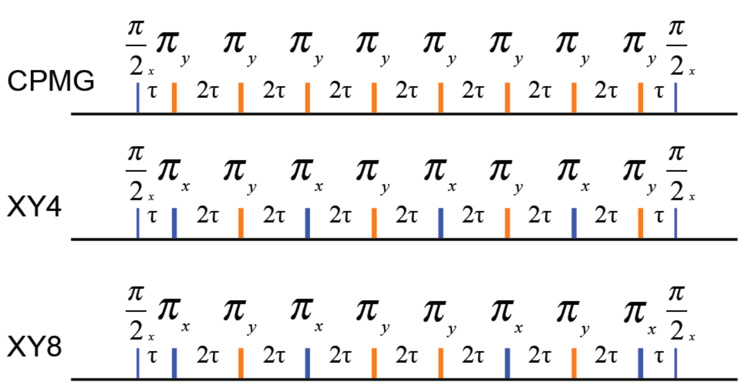
Chen et. al. PNAS (2022)

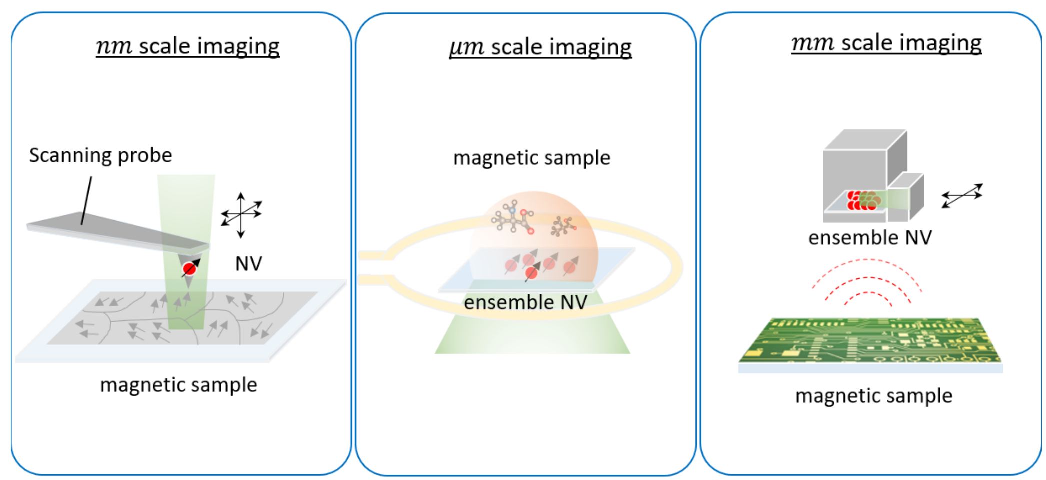


McCoey et. al. Small (2020)

Summary

- 스핀 큐비트 기반 양자센싱 기초 원리 (e.g. Ramsey, echo, dyanimcal decoupling, etc.)
- 다이아몬드 NV 센터 소개
- NV 센터 기반 양자 센싱 소개
- NV 센터 기반 양자 이미징 소개





Summary

- Quantum sensing, quantum metrology (양자센싱, 양자계측)
- 측정은 모든 물리 실험의 기본
- 양자센싱 및 이미징은 양자현상에 기반한 물리 실험의 새로운 방법론 제공
- 중시계 등 다양한 기초·응용 물리 실험에 활용 가능