Bruce and Electric Dipole Spin Resonances

Old Days' Story
and

PRL 99, 246601 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Hyperfine-Mediated Gate-Driven Electron Spin Resonance

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Supported by Rutherford Professorship, Loughborough University, UK

Magnetic Excitations in Semiconductors - Bridges to the Next Decade

McCombe Fest-Symposium, Buffalo, March 6 – 8, 2008

Beginning of the Story: 40 years ago

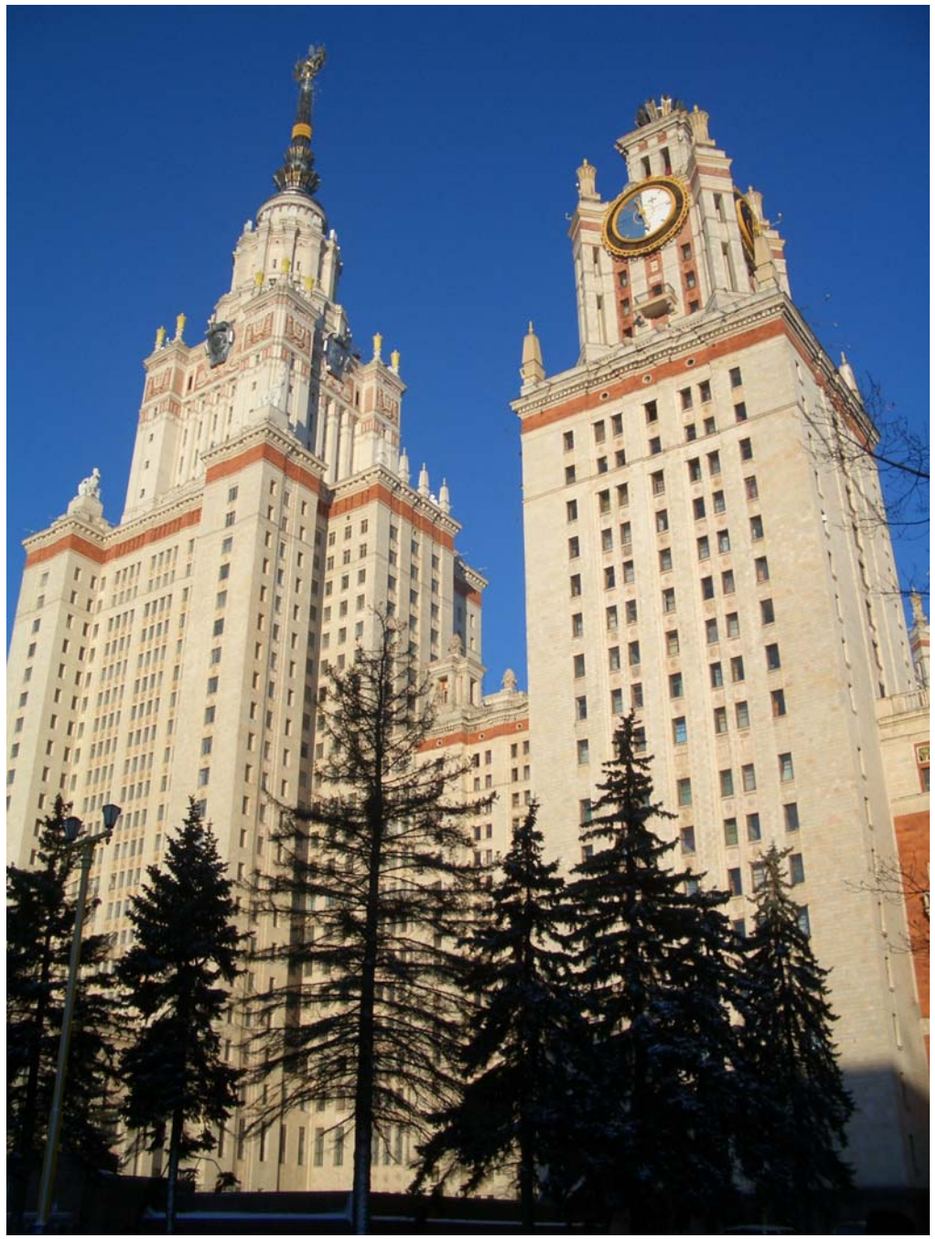
Ninth International Conference on Physics of Semiconductors

Moscow, Summer 1968

VOLUME 18, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 1967

COMBINED RESONANCE AND ELECTRON g VALUES IN InSb*

B. D. McCombe,† S. G. Bishop,† and R. Kaplan
Naval Research Laboratory, Washington, D. C.
(Received 24 March 1967)

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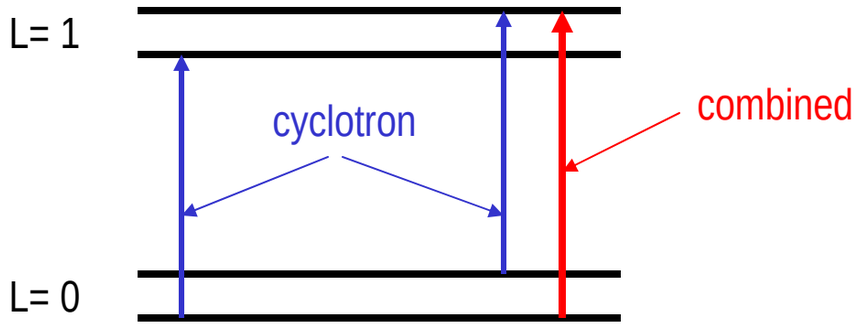
In that paper, McCombe, Bishop, & Kaplan (PRL 1967) reported for InSb:

1. **Discovery** of Electric Dipole transitions at the frequencies $h\nu_c$ and $\boldsymbol{h\nu_c+h\nu_s}$
First the Cyclotron Resonance, second the Combined Resonance



Spin transitions driven by ac electric field

2. Using them as an instrument for measuring g-factor at L=0 and L=1 Landau levels

3. Establishing a specific mechanism of the Combined Resonance (will come to this point)

Afterwards Bruce made the Combined Resonance a powerful tool for measuring g-factors and electron-phonon coupling constants, discovered it in $Hg_{1-x}Cd_xTe$ (McCombe & Kaplan, PRL 1968), etc.

Bruce proved the reality of the Combined Resonance convincingly

In modern terms:

Electric Dipole Spin Resonances (EDSR)

Why proving was important: Principle and Parameter Values

ER, Sov. Phys. Solid State **2**, 1109 (1960)

The prediction that EDSR can be orders of magnitude stronger than the magnetically driven spin resonance was accepted skeptically, in particular by the ESR community

Wurtzite → Zinc blende: bulk A_3B_5

Wurtzite → Heterostructures, 2D

Change from 3D to lower dimensions and confined systems was inspired by two papers:

Stormer, Schlesinger, Chang, Tsui, Gossard, Weimann, PRL **51**, 126 (1983)
Cyclotron resonance, 2D holes

Stein, von Klitzing, Weimann, PRL **51**, 130 (1983)
Spin resonance, 2D electrons

Bychkov & ER, Sov. Phys. - JETP Lett. {\bf 39}, 78-81 (1984)

Zero-order approach to the description of both systems

Multiplicity of EDSR mechanisms: Great challenge

A_3B_5, bulk 3D, **intrinsic mechanisms**:

$$H_{SO} \propto \boldsymbol{\sigma}\cdot\boldsymbol{\kappa}, \kappa_z = k_x k_z k_x - k_y k_z k_y, \mathbf{k} \to \mathbf{k} - e\mathbf{A}/\hbar c$$ Dresselhaus 1955

Dobrowolska, Chen, Furdyna, Rodriguez, PRL **51**, 134 (1983)

$$H_{SO} \propto \mathbf{E}\cdot \mathrm{r}_{SO},\ \mathrm{r}_{SO} \propto \boldsymbol{\sigma}\times\mathbf{k}$$ Yafet 1963

Discovered by McCombe et al. 1967

Extrinsic mechanisms: puzzling results on n-InSb, Bell, PRL 9, 52 (1962)

compensated n-Ge, Gershenson et al. JETP Lett. 12, 139 (1970)

Inhomogeneous Zeeman mechanism of spin-orbit coupling, $H_Z = g(\sigma\cdot\mathbf{B}(\mathbf{r}))$

Pekar & ER, 1965

Reviewed by ER & Sheka, 1991

Nanoscopic EDSR in a Double Quantum Dot

Single electron operation

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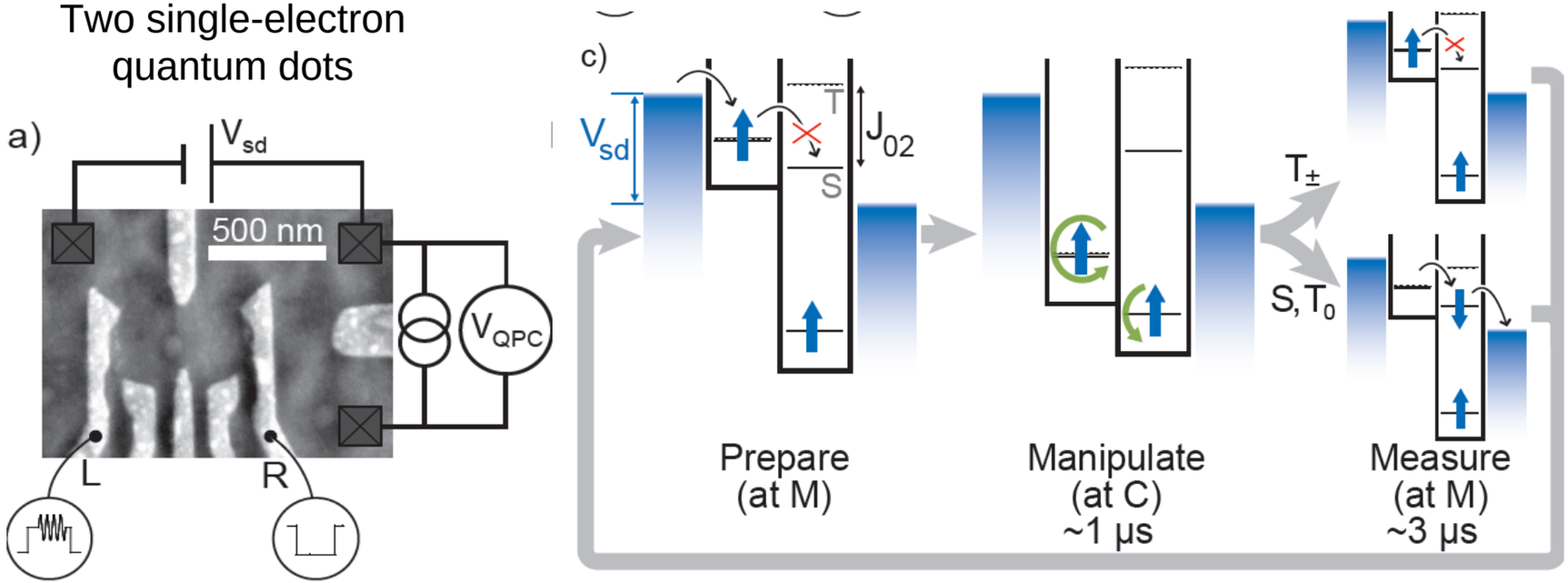
(Received 3 July 2007; published 13 December 2007)

Two single-electron quantum dots



Two competing mechanisms of EDSR in a quantum dot

1. Time dependent hyperfine interaction – a new mechanism of EDSR

$H_{hf}(t)$, in the vibrating quantum dot frame

$$H_{\mathrm{hf}}(t) = A\sum_j \delta(\mathbf{r}+\mathbf{R}(t)-\mathbf{r}_j)(\mathbf{I}_j\cdot\mathbf{S}),\ \ \mathbf{R}(t) = -e\mathbf{E}(t)/m\omega_0^2$$

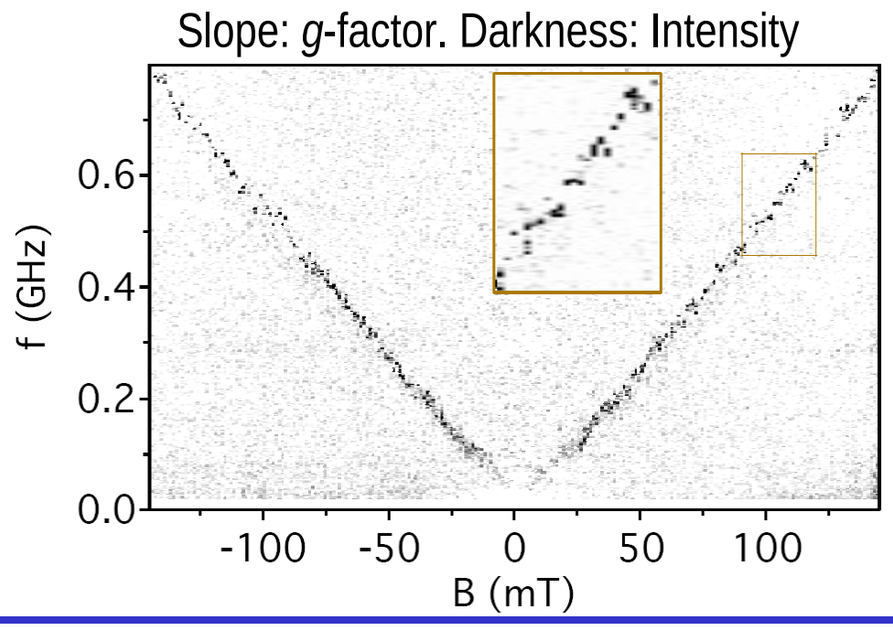
Rabi frequency $\Omega_R = \dfrac{eEA}{\hbar^2\omega_0}\sqrt{\dfrac{I(I+1)n_0}{8\pi d}}$

EDSR intensity and Ω_R do not depend on B because t - inversion is violated

2. Spin-orbit coupling

$$H_{\mathrm{SO}} \propto (\boldsymbol{\sigma}\,\hat{\gamma}\,\mathbf{k})$$

EDSR intensity is proportional to B^2 because of the Kramers theorem

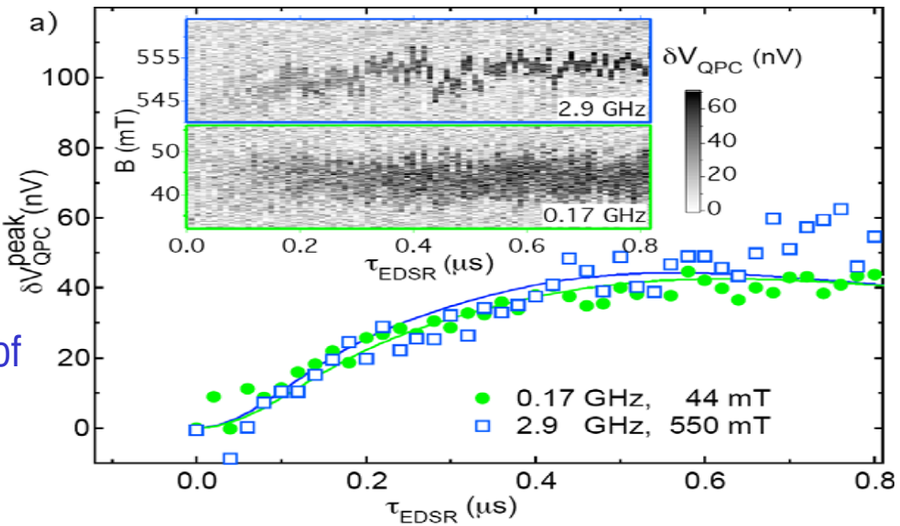


Experimental data *vs* semiclassical theory

Dependence of the current on the pulse duration τ_{EDSR}

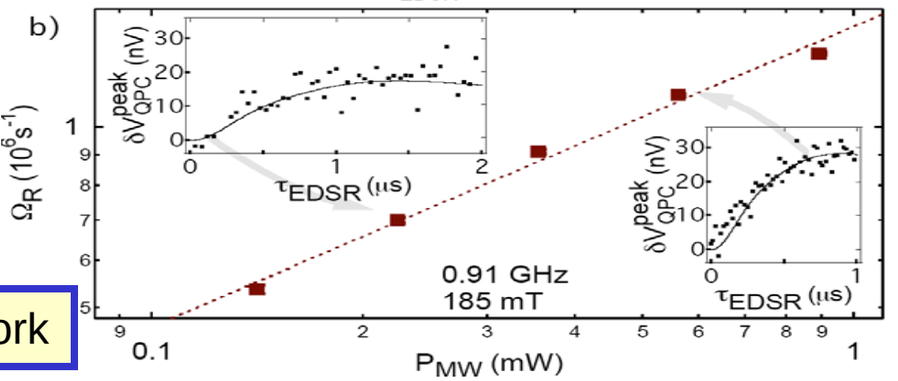
From the curve shape, Ω_R can be found

Notice: There are no Rabi oscillations because of the averaging over nuclear spin configurations



Rabi frequency dependence on the microwave power P_{MW}

$$\Omega_R \propto \sqrt{P_{MW}}$$



Hyperfine mechanism of EDSR is on work

At larger fields B, spin-orbit mechanism dominates, Nowack *et al*., Science 318, 1430 (2007)

Conclusions

(i) Old Days' reminiscences,

(ii) Seminal paper by Bruce et al. (1967),

(iii) Multiplicity of EDSR mechanisms,

(iv) Related challenges,

(v) Nanoscopic single-electron EDSR in quantum dots