Developing Quantum Logic Gates: Spin-Resonance-Transistors

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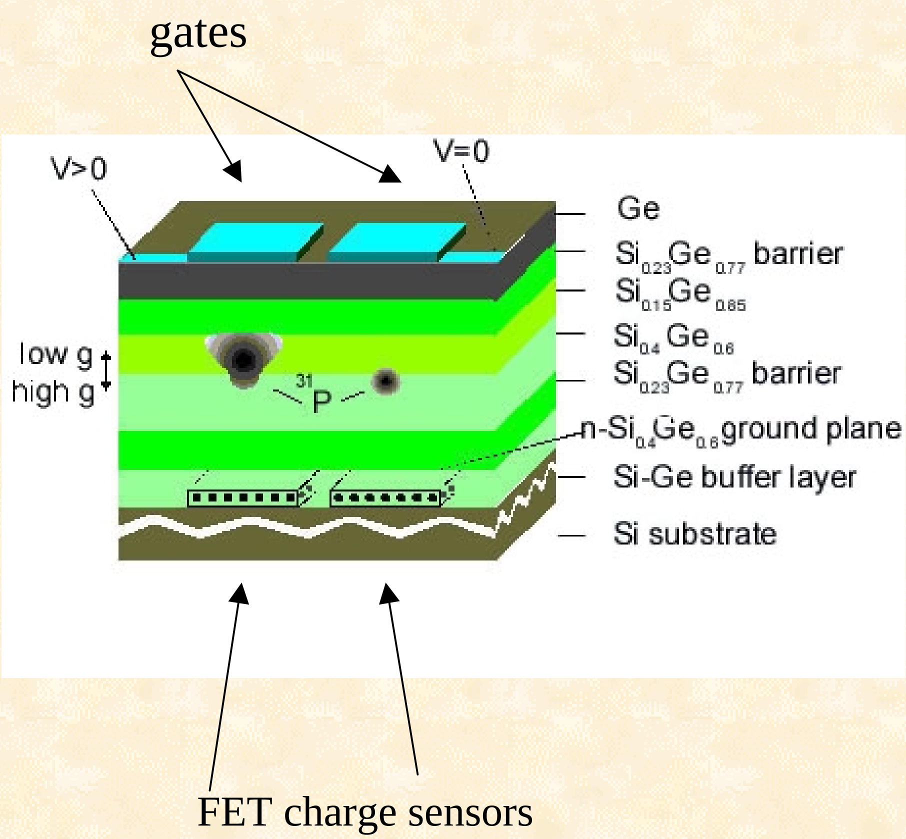
SRT: a Field Effect Transistor in which the channel resistance monitors electron spin resonance, and the resonance frequency is in turn controlled by the gate voltage.



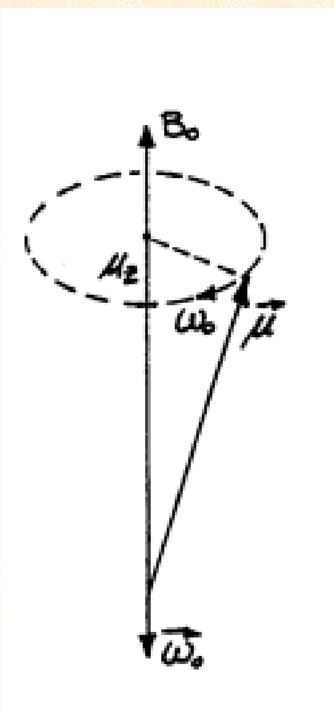
Single qubit operations

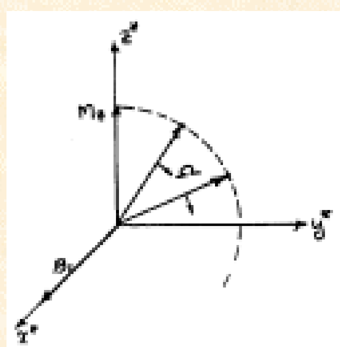
σ_x^α *and* σ_z^α

* Each SRT can be tuned, *individually*, in and out resonance with the global microwave field by the gate-voltage

* arbitrary rotations can be performed by varying the gate pulse width at electron-spin-resonance

ex: $\pi/2$ pulse ($\Delta t = \pi/2\gamma B_{AC}$)





$\mathbf{B}^* = B_{AC}\boldsymbol{i}^*$

the spin process about this field at a rate

$\Omega = \gamma B_{AC}$

in a rotating coordinate frame:

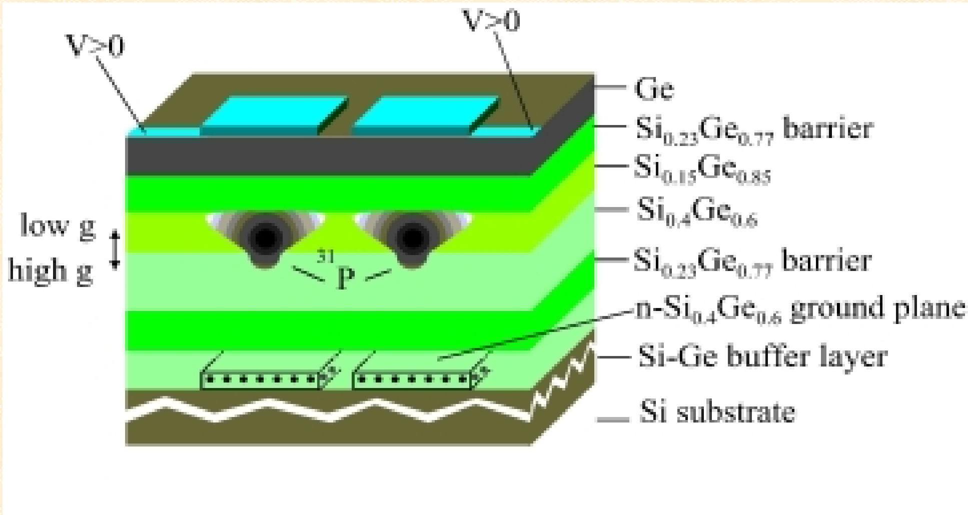
$\mathbf{B}^* = B_{AC}\boldsymbol{i}^* + (B_{DC} - \omega/\gamma)\boldsymbol{k}^*$

$$\mu \times \mathbf{B} = d\,\mathbf{J}/dt$$

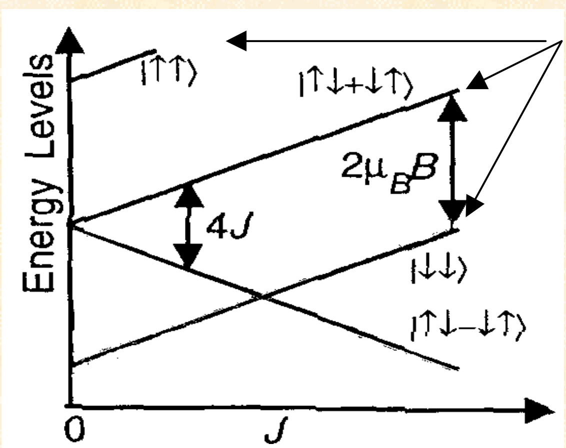
$\omega_0 = \gamma B_{DC}$

Two-qubits operations

Swap -S^{α}



two-qubits Wavefunction entanglement



Triplet states

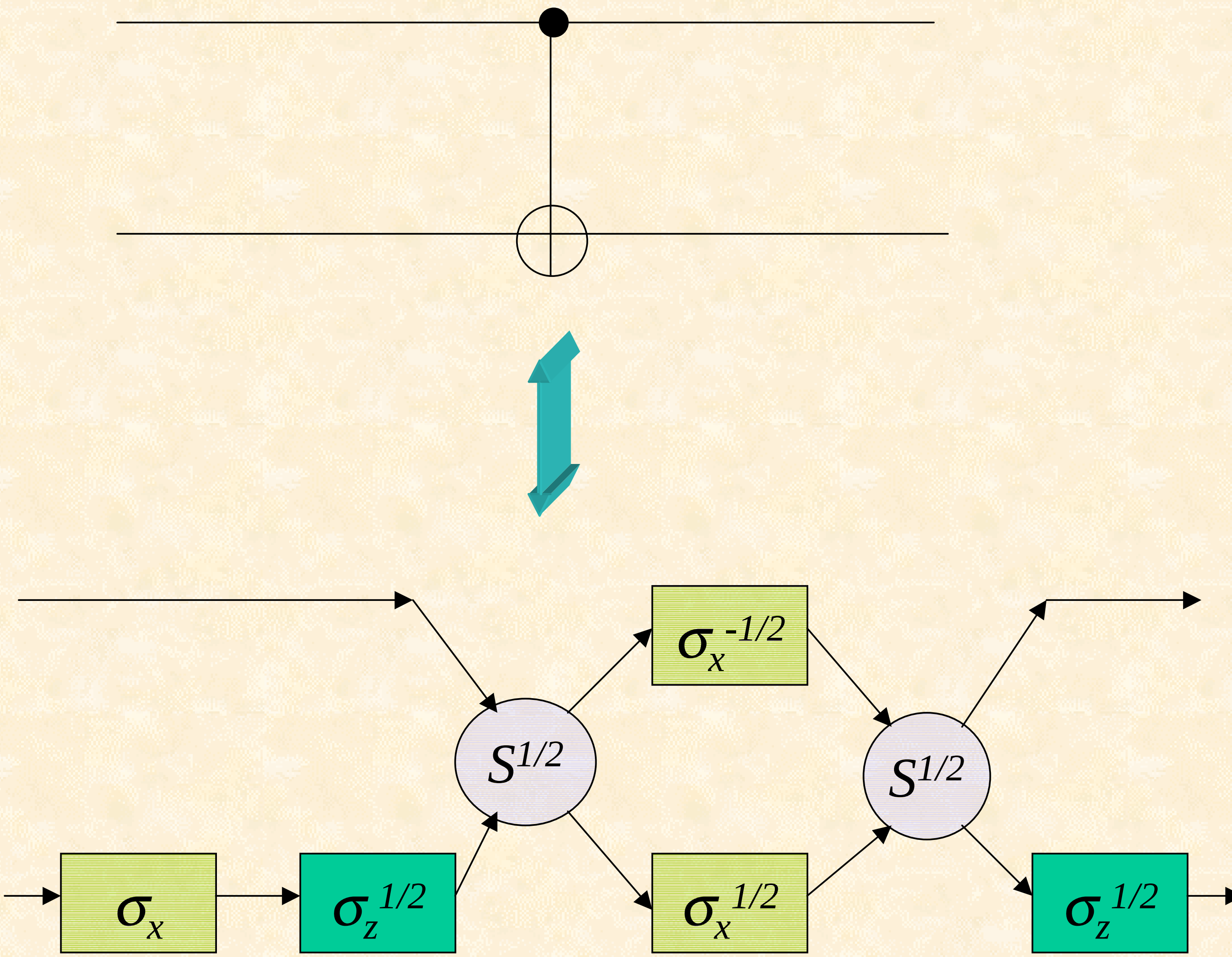
Singlet state

$$\frac{4J(r)}{h} \approx 1.6\,\frac{q^2}{\varepsilon a_B}\left(\frac{r}{a_B}\right)^{5/2} \exp\left\{\frac{-2r}{a_B}\right\},$$

* J-exchange interaction depends on the overlap of the wavefunctions which is controlled by gate voltages

* At off-resonance, the wavefunction can be controlled by gate voltages as the gate pull the electron away from the nucleus: Coulomb potential is weakened → a_B increases → J-exchange overlap turns on

To implement a CNOT gates:



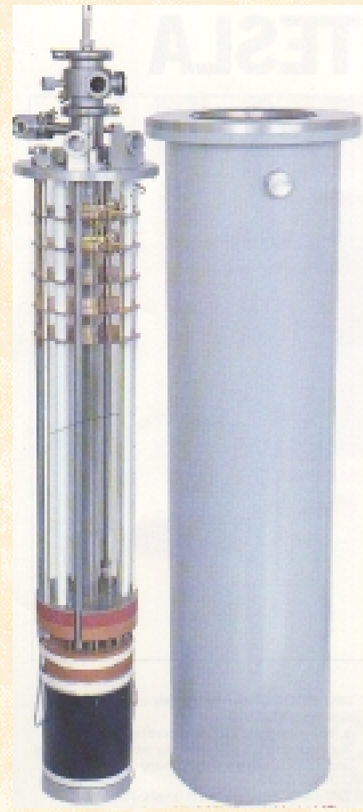
A precise electrical control of the ESR (the resonance frequency and the pulse timing) is need

Environment for the devices:1.2 K, 2-3 T

Field and temperature considerations:

* long T_2

* initializations



long term cryogenic solutions for military applications:

* use compact close-cycle refrigerator

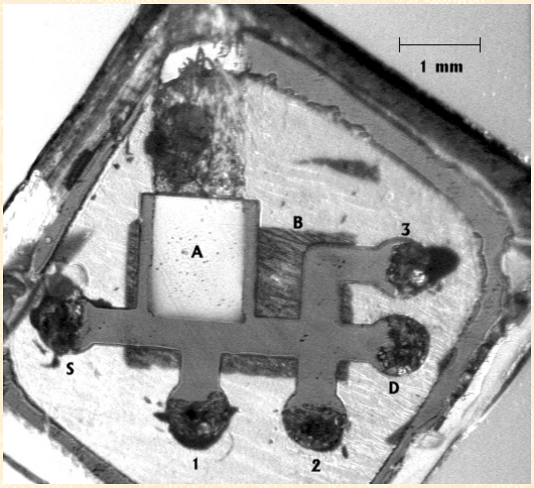
* use small high-field permanent magnet

First-stage experiments:

*** to electrically detect electron-spin-resonance (ESR) of few spins (conventional ESR requires 10^{12} electrons)**

*** to gain control of ESR by gate**

*** to explore the potential of using nuclear spin for quantum memory**



Using GaAs/AlGaAs hetero-structures first:

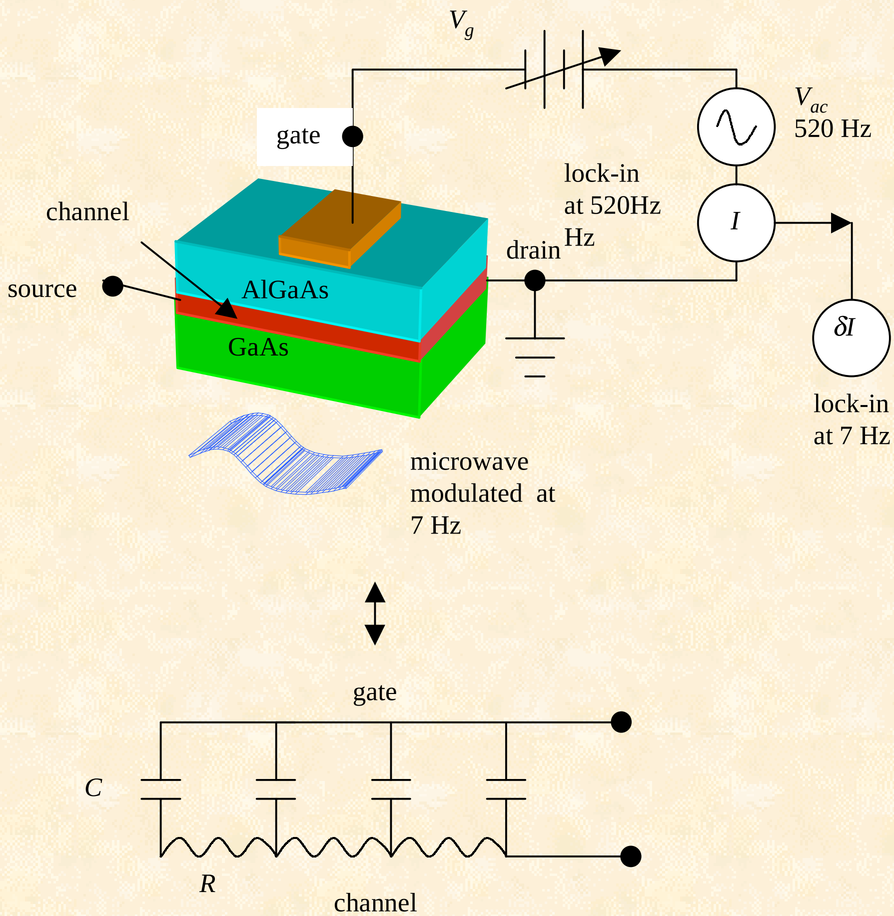
* direct gap material (easy to integrate with single photon emission and detection)

* reasonably long relaxation time: T_2^* about 100 nS

* clean system: high mobility (10^6 cm^2/V-Sec, mean-free path of 1-micron)

* vast amount of knowledge about the electrons in the quantized magnetic-field from the research of quantum Hall effects

measurements



$$I = V_{ac}\left\{\frac{\tanh\ \alpha}{\alpha}\right\},\ \alpha \equiv \sqrt{j\omega RC}$$

$$for\ \omega RC << 1$$

$$I(0) \propto R$$

$$I(90^{o}) \propto C$$

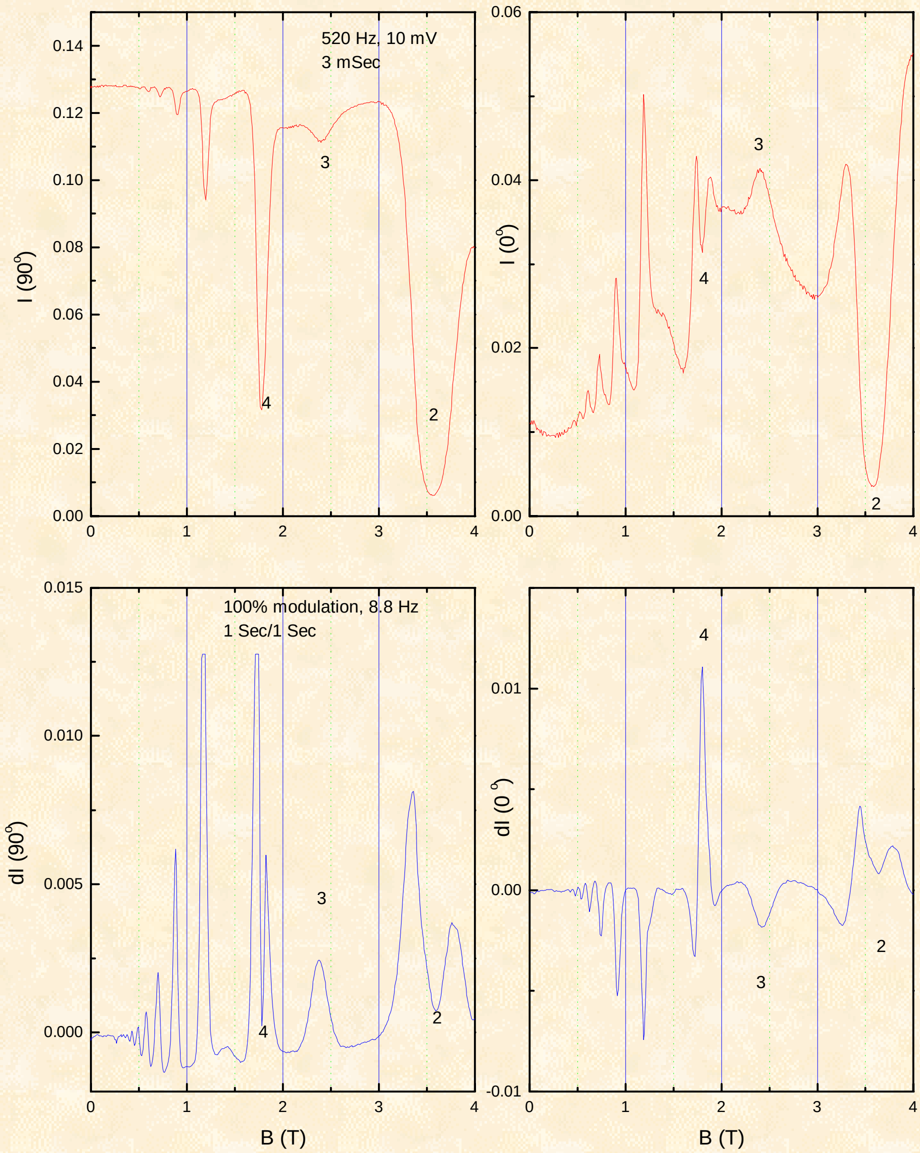
$$1/C = 1/C_{geometric} + 1/C_Q$$

$$C_Q \equiv e^2\left(\frac{\partial n}{\partial \mu}\right),$$

$$\frac{\partial n}{\partial \mu} \equiv density - of - states$$

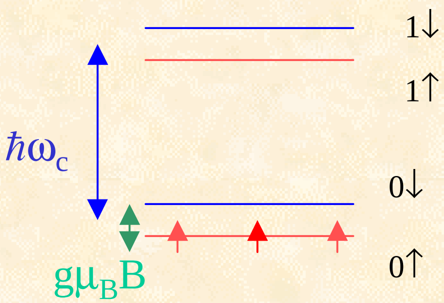
13 GHz, 15 dBm

1.3 K, 0.5 T/min



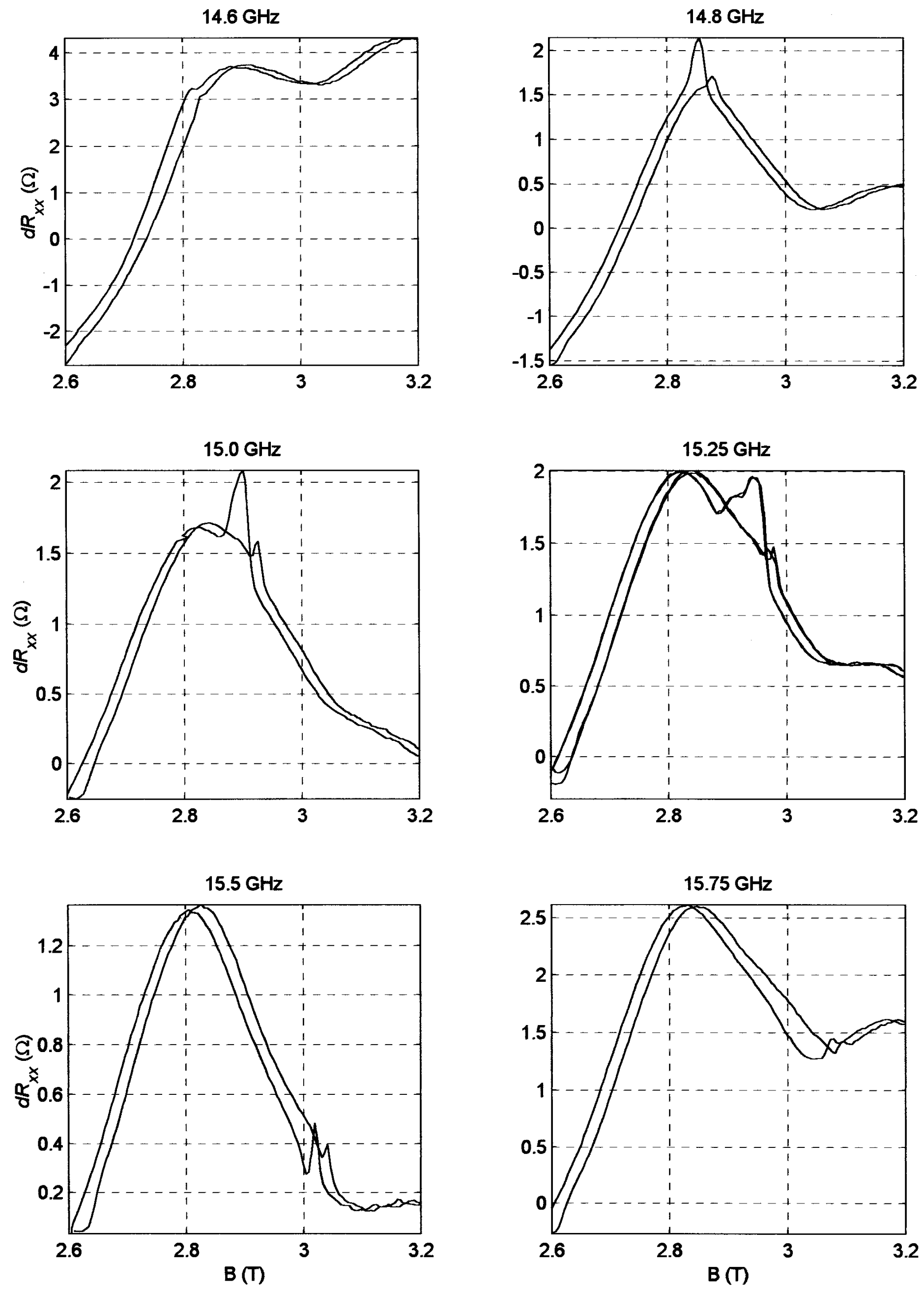
capacitance and resistance

changes of capacitance and resistance due to microwave radiation (non-resonant)



a spin-1/2 system at odd filling factors

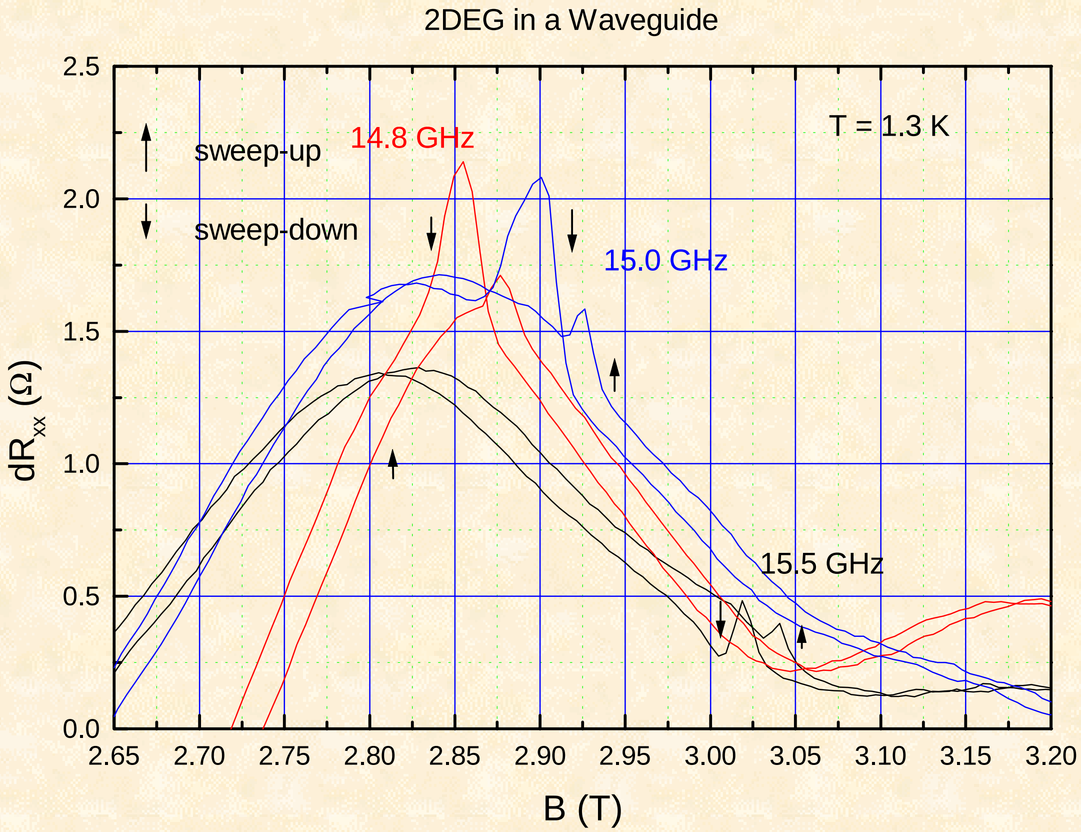
$$E=(N+1/2)\,\hbar\omega_c+g\mu_B B$$



* detected ESR in different samples with 10^5-10^{10} spins

* line-width 50 MHz (for field scan-up)

* also detected in capacitance (spin-flip→change DOS)



* Overhauser shift due to the hyperfine interaction

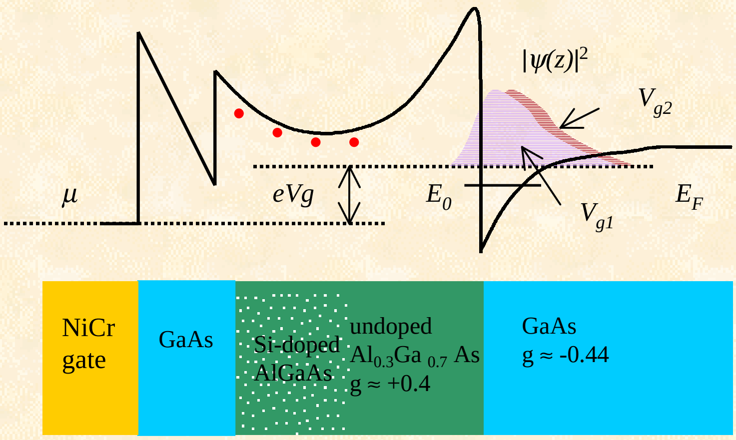
$$A\vec{I} \bullet \vec{S} = A\{\frac{1}{2}(I_+S_- + I_-S_+) + I_zS_z\}$$

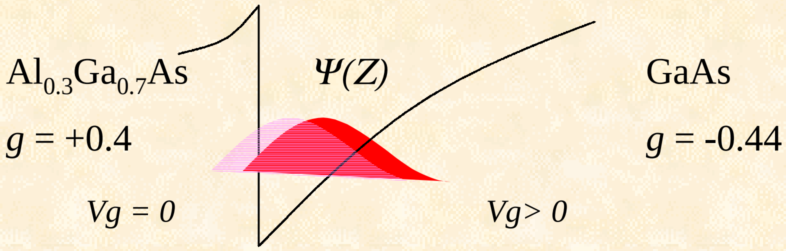
DNP by a mutual flip of electron and nuclear spins

* long nuclear relaxation (~ 700 Sec) showing potential for quantum information storage

Gate Controlled ESR

(g-factor engineering)



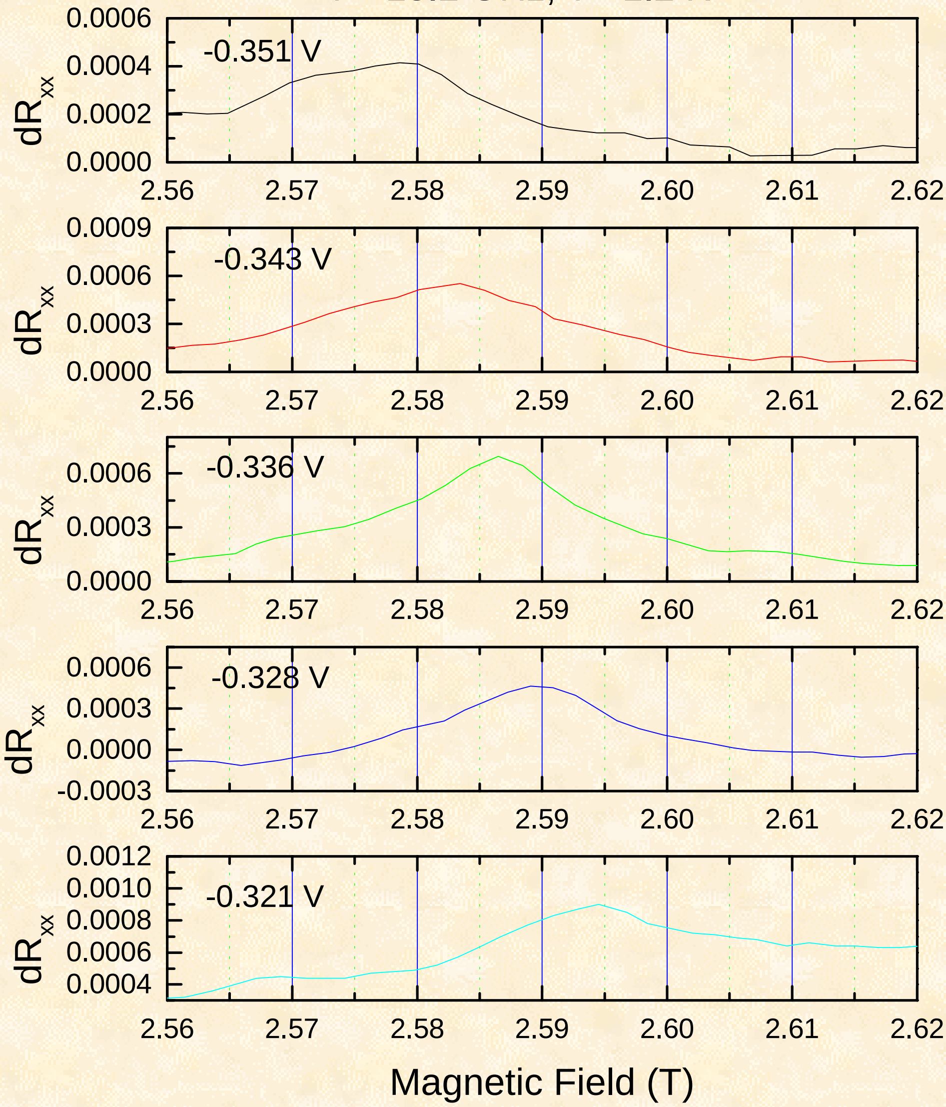


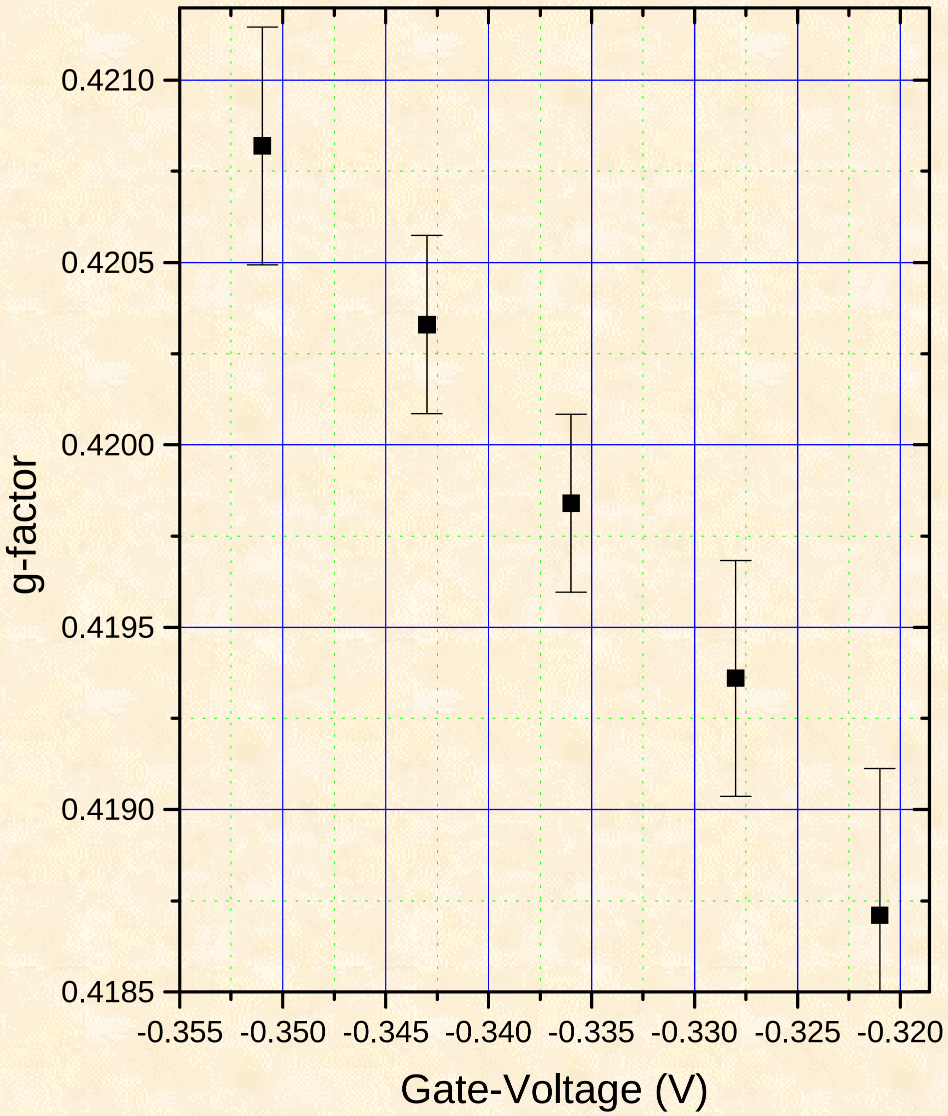
$$g_{eff} = \int g(z)|\psi(z)|^2 dz$$

$$\psi(z) = f(V_g)$$

ESR spectra at different gate-voltages

f = 15.2 GHz, T =1.2 K



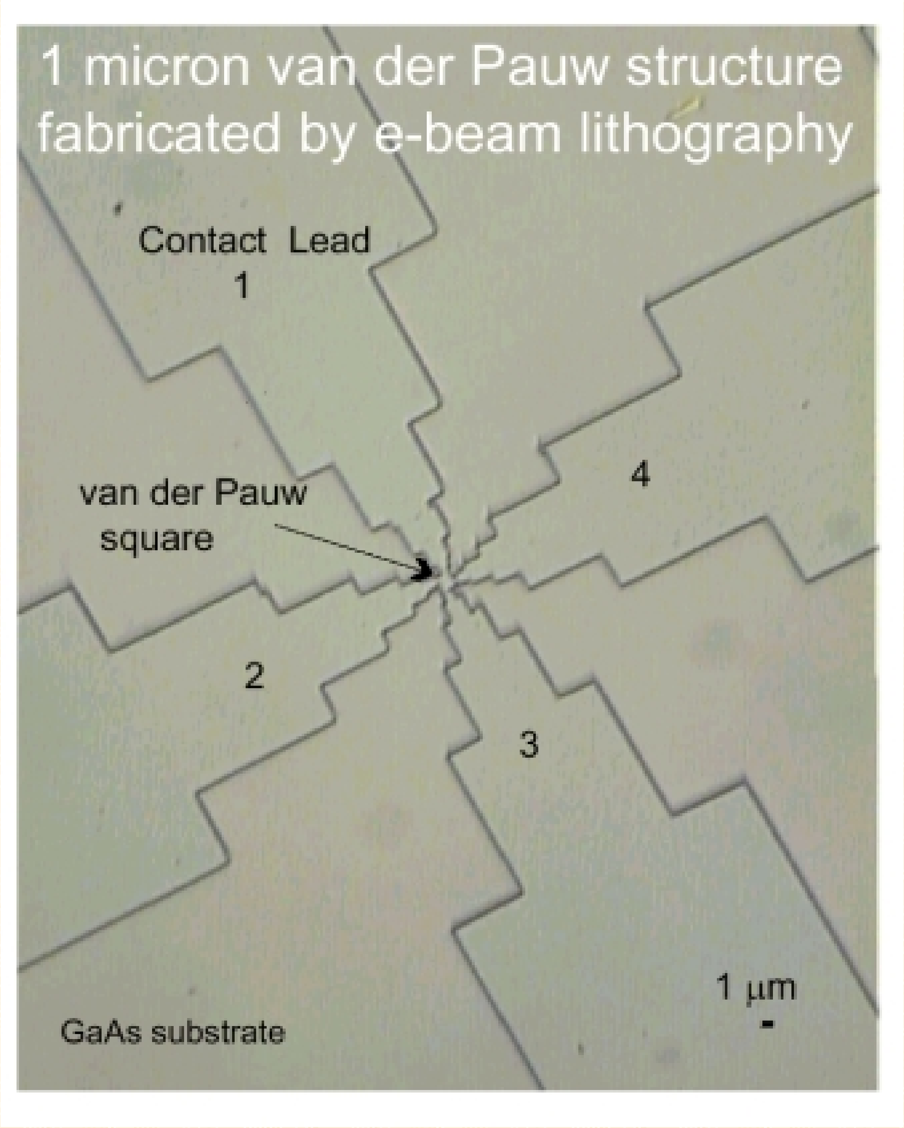


0.4210
0.4205
0.4200
0.4195
0.4190
0.4185
g-factor
-0.355
-0.350
-0.345
-0.340
-0.335
-0.330
-0.325
-0.320
Gate-Voltage (V)

Next:

1. ESR detection with small FET

(100-1000 electrons in the channel)



Structures have been fabricated in UCLA Nano-Structure Research Lab. for the experiments

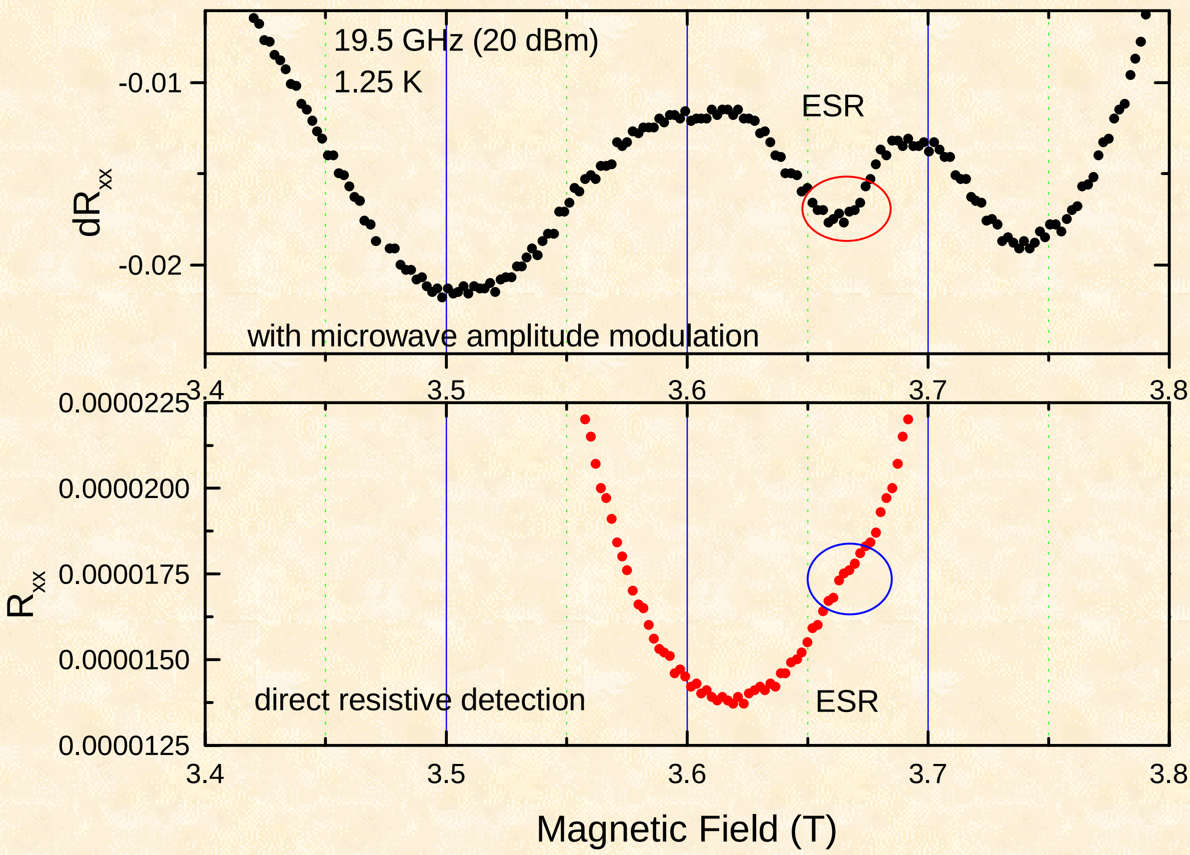
Next:

2. Time-resolved detection of ESR

use high Q-cavity to boost up B_{ac} : $(1/(\gamma B_{ac})>>T_2, T_1$

* eliminate lock-in detectors for detection, make device application practical

* do time-resolved ESR (ex. to measure the spin-flip time T_1)



* ESR can be detected with large microwave power

A resonant cavity is being fabricated