JST-DFG Workshop on Nanoelectronics
Aachen, Germany, March 5-7, 2008

# Electrical control of magnetism in semiconductors

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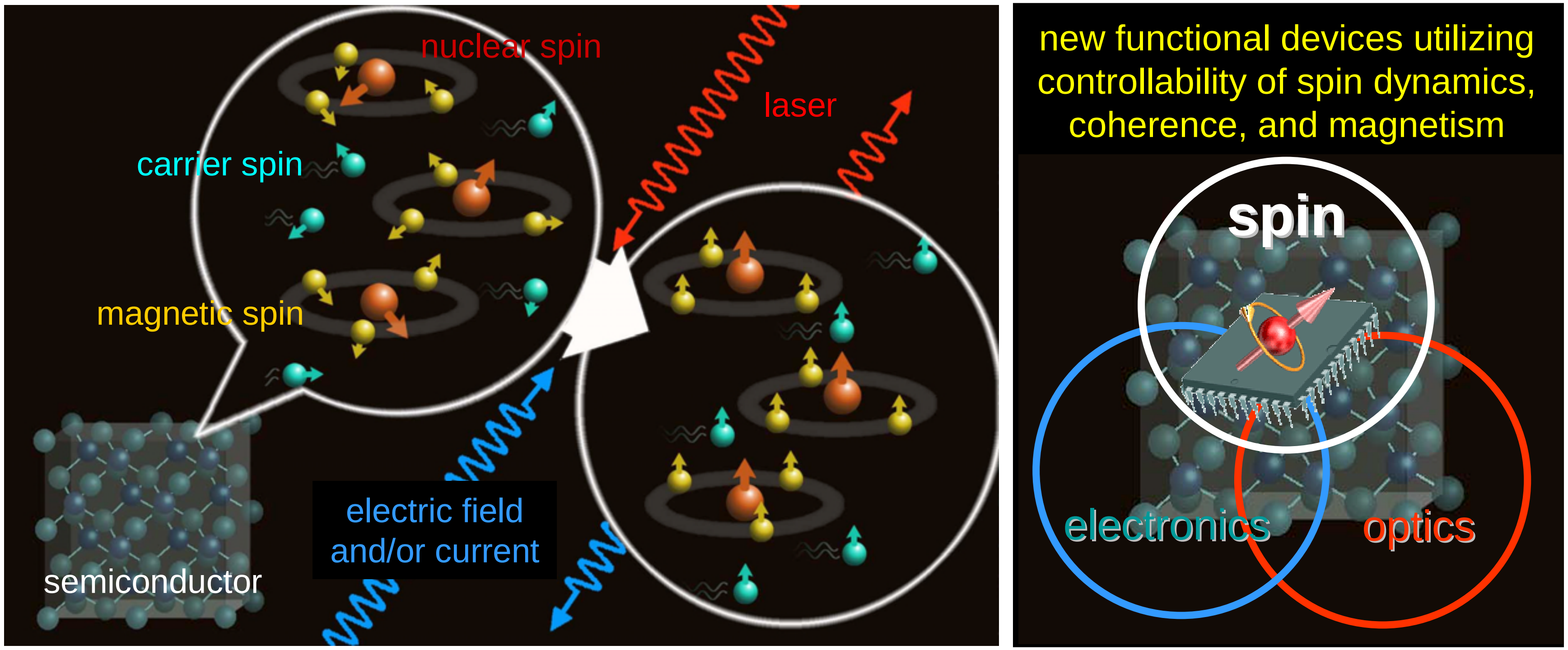
## Outline

- Introduction
  (field effect transistor with a magnetic semiconductor channel)
- Thickness dependence
- Mn composition dependence
- Summary

Discussion with M. Sawicki and T. Dietl (Polish Academy of Sciences)

## Semiconductor Spin-electronics (Spintronics)

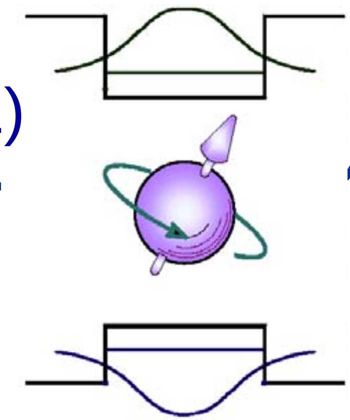
**Spin-related phenomena** in semiconductors →
an additional degree of freedom (spin + charge → **spintronics**)

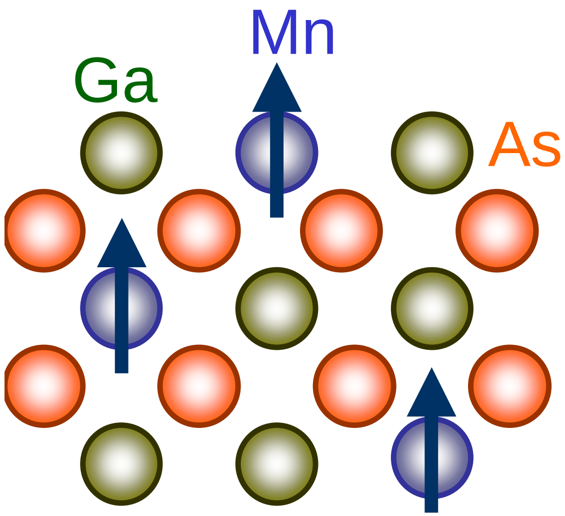


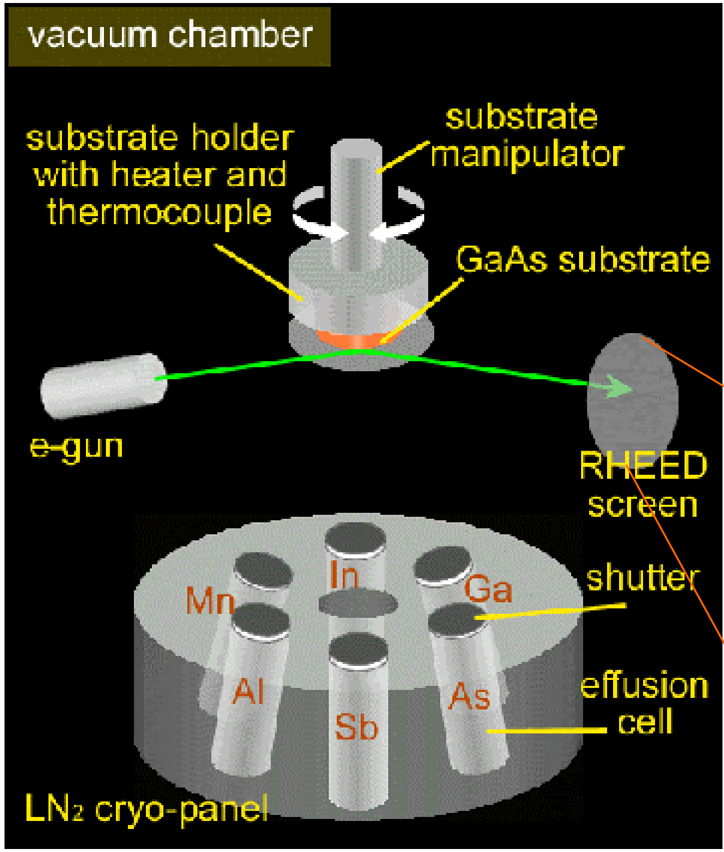

In order to enhance spin-related phenomena in semiconductors
· alloy system with host semiconductor and guest magnetic ion
**(diluted magnetic semiconductors; DMSs)**
⇒ **Multifunctional materials**

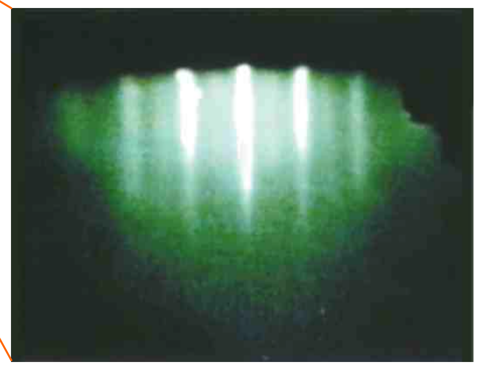
# III-V Based Magnetic Semiconductors

· Combine present day electronic device materials with magnetism
· Low solubility of magnetic elements overcome by
*low-temperature molecular beam epitaxy* (LT-MBE)





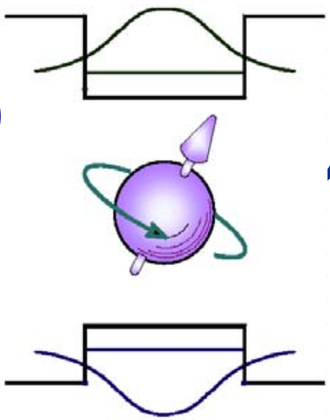



New materials can be synthesized under non-equilibrium growth condition

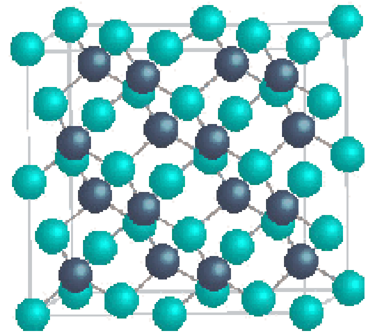
# III-V Based Magnetic Semiconductors

- Combine present day electronic device materials with magnetism
- Low solubility of magnetic elements overcome by
  *low-temperature molecular beam epitaxy* (LT-MBE)



## First III-V Based Magnetic Semiconductor

(In,Mn)As: H. Munekata *et al*., Phys. Rev. Lett. **63**, 1849 (1989).

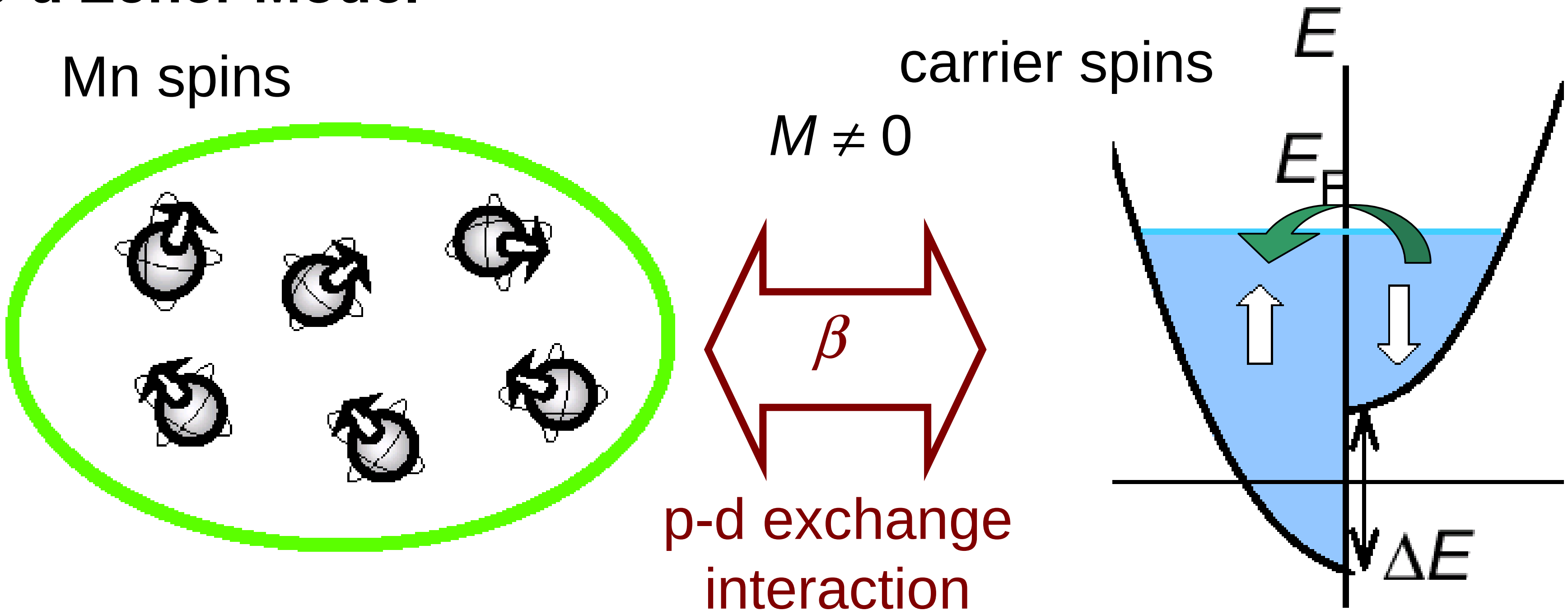


## Ferromagnetism

(In,Mn)As: H. Ohno *et al*., Phys Rev. Lett. **68**, 2664 (1992).
(Ga,Mn)As: H. Ohno *et al*., Appl. Phys. Lett. **69**, 363 (1996).

Mn acts simultaneously as an acceptor and as a magnetic spin

## p-d Zener Model




Interaction (p-d exchange interaction) between holes and Mn spins induces the spin-splitting of valence band

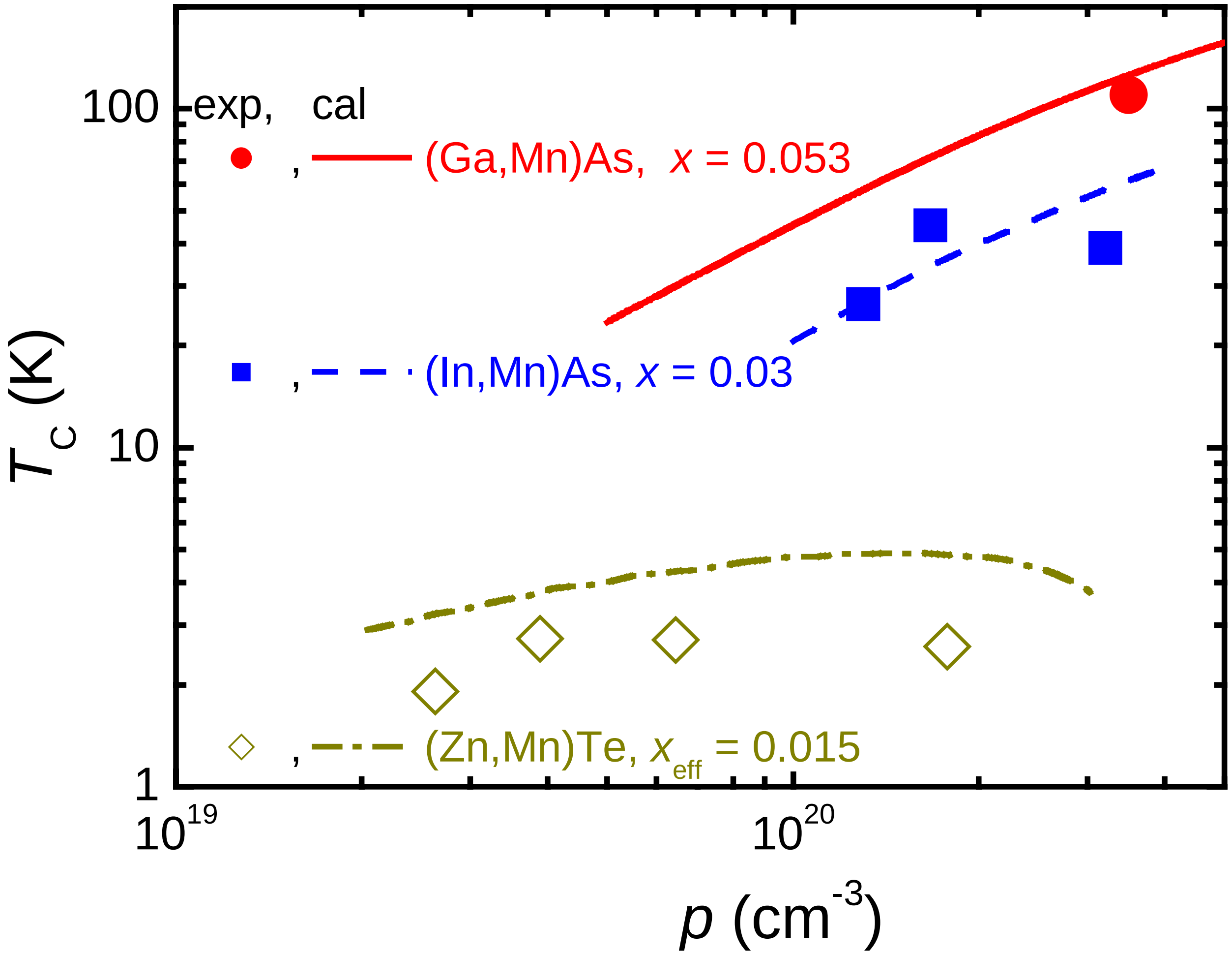
⇓

Energy gain by repopulation of holes between spin subbands stabilizes ferromagnetism

Curie temperature: $T_c = \dfrac{x N_0 S(S+1) A_F \rho_S (E_F) \beta^2}{12 k_B}$

T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science **287**, 1019 (2000).
T. Dietl, H. Ohno, and F. Matsukura, Phys. Rev. B **63**, 195205 (2001).

# Comparison of Experimental and Calculated $T_C$

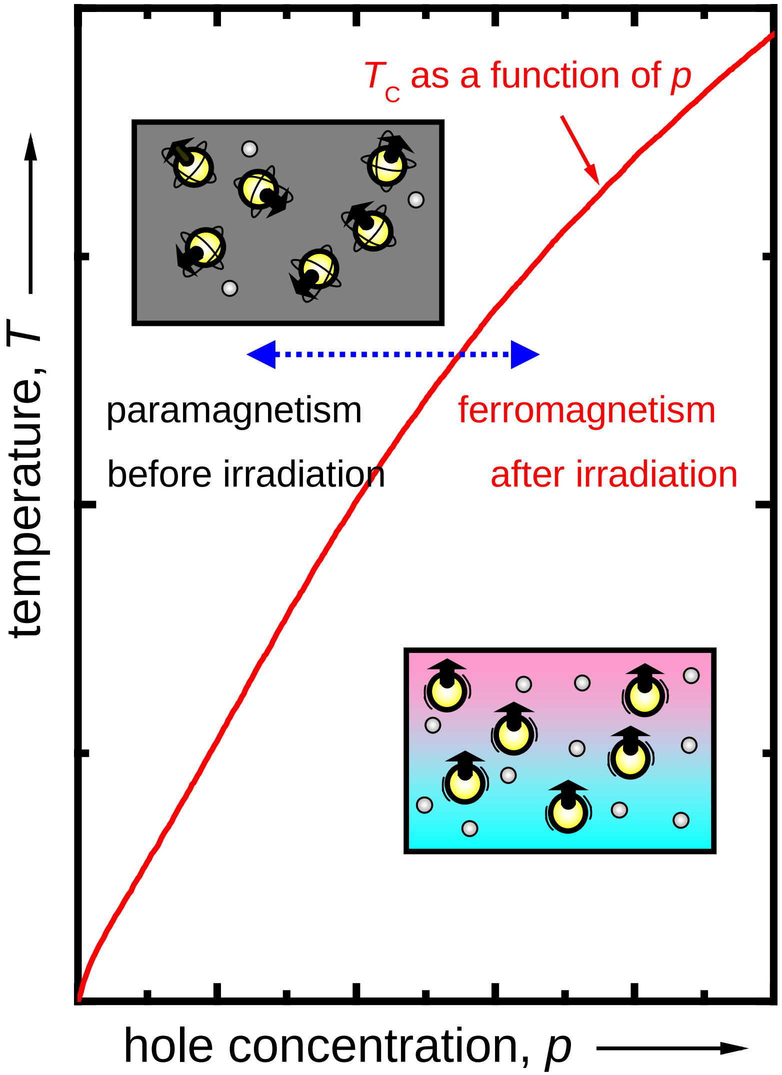



larger $T_C$ for larger $p$

quantitative agreement between experiment and calculation

exp.: (Ga,Mn)As:T. Omiya *et al*., Physica E **7**, 976 (2000).
(In,Mn)As: D. Chiba *et al*., J. Supercond. and Novel Mag.16, 179 (2003).
(Zn,Mn)Te: D. Ferrand *et al*., Phys. Rev. B **63**, 085201 (2001).

# Control of magnetism of ferromagnetic semiconductors by external means




optical means

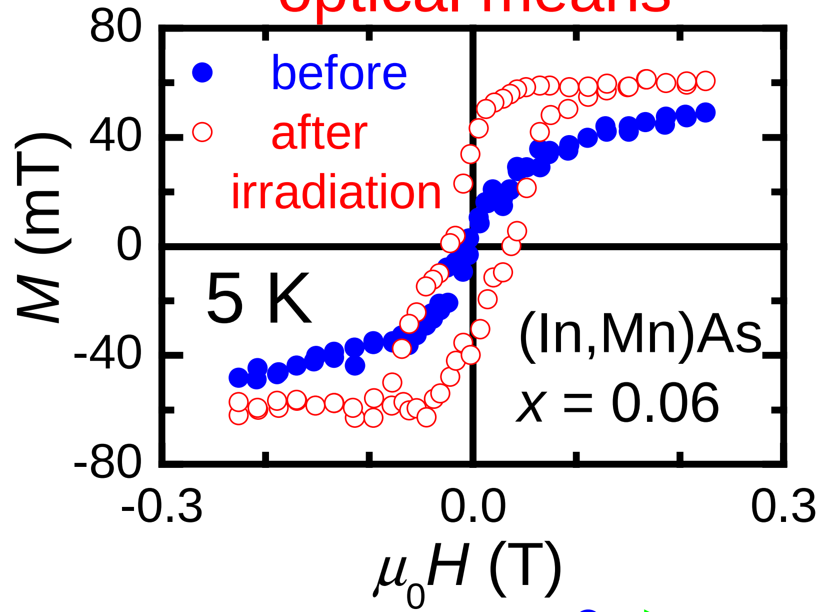
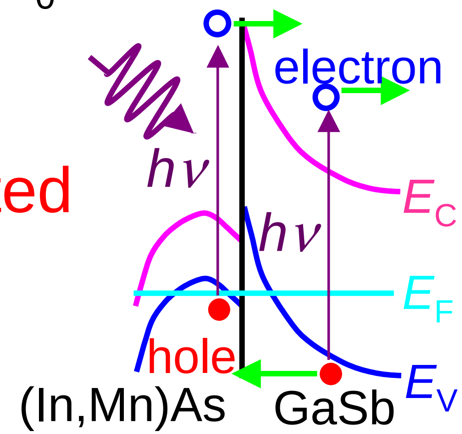


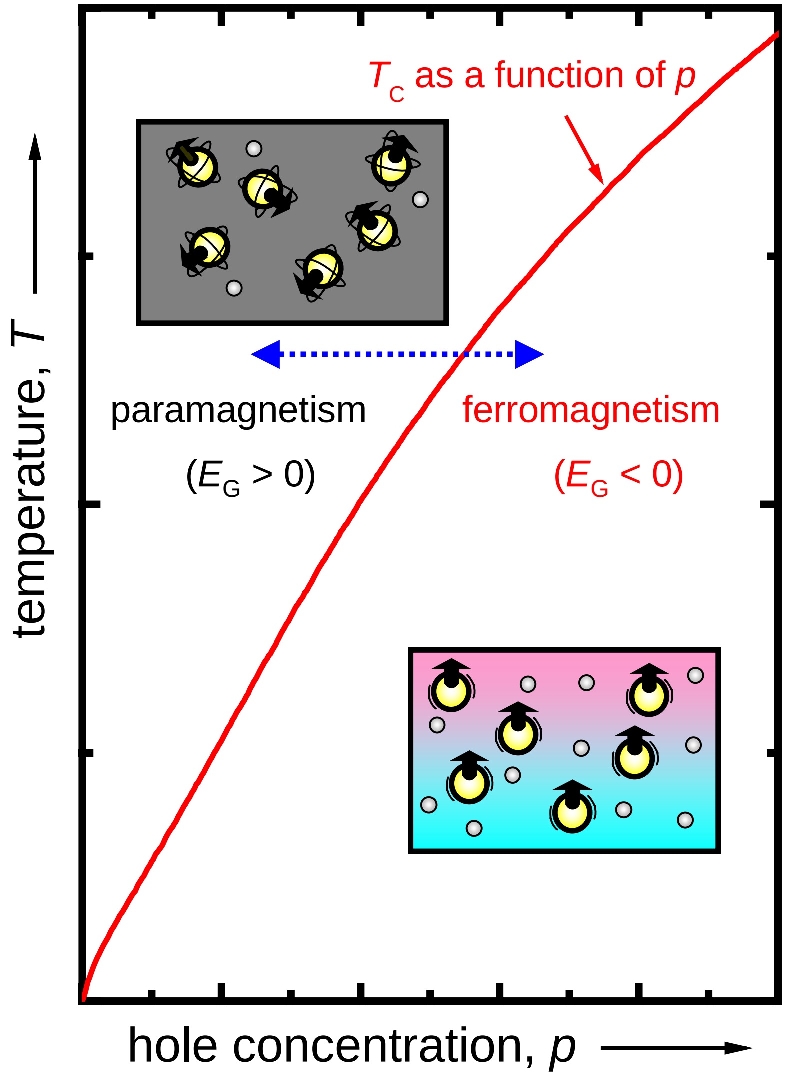

photo-generated carriers

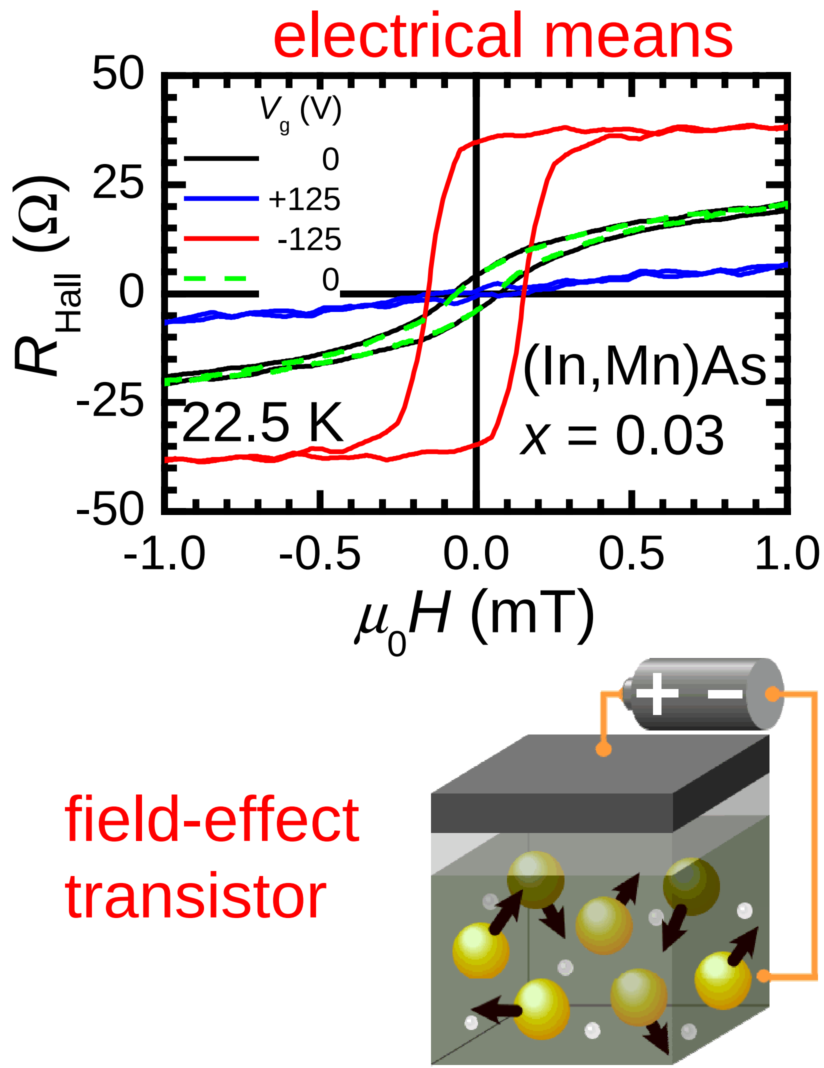



isothermal control of magnetism

S. Koshihara *et al*., Phys. Rev. Lett. **78**, 4617 (1997).

# Control of magnetism of ferromagnetic semiconductors by external means




isothermal control of magnetism

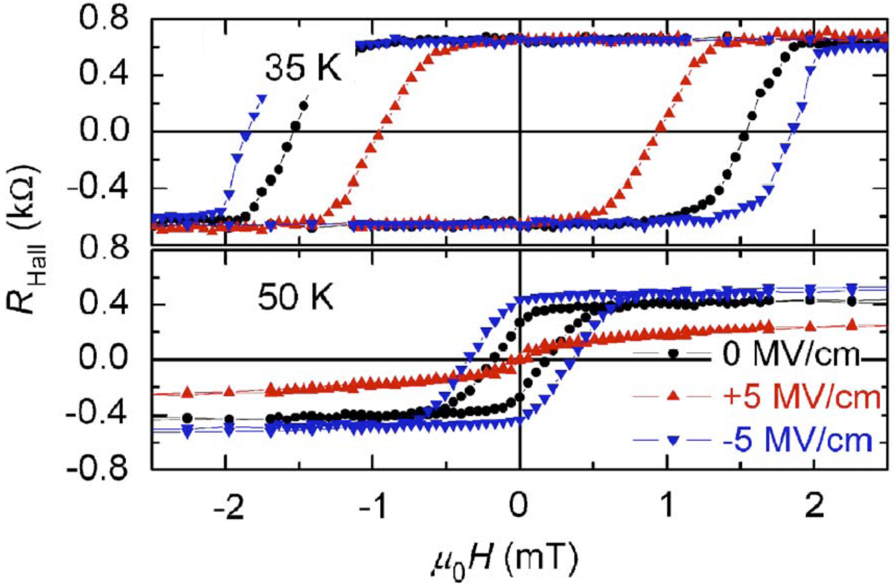
H. Ohno *et al*., Nature **408**, 944 (2000).

# Previous result on FET with (Ga,Mn)As channel

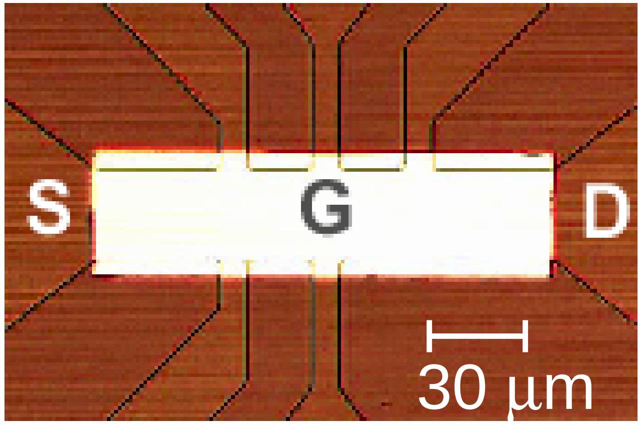
sample structure

| | | |
|---|---|---|
| gate metal | 100 nm | Au / Cr |
| gate Insulator | 50 nm | $Al_2O_3$ |
| channel | 7 nm | $Ga_{0.863}Mn_{0.047}As$ |
| buffer | 7 nm | GaAs |
| | 30 nm | $Al_{0.8}Ga_{0.2}As$ |
| | 500 nm | $In_{0.13}Ga_{0.87}As$ |
| | 100 nm | GaAs |
| substrate | S.I. GaAs (001) sub. | |

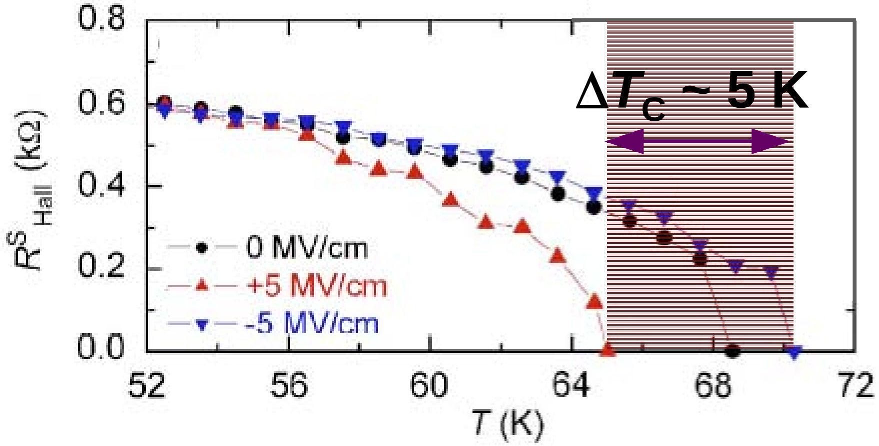
Hall resistance




FET device with Hall-bar shape




Arrott-plot analysis




D. Chiba *et al*., Appl Phys Lett **89**, 162505 (2006).

## This work

1. FETs with (Ga,Mn)As channel and gate insulator ($Al_2O_3$ or $HfO_2$ ) deposited by atomic layer deposition (ALD)

Atomic Layer Deposition (ALD)

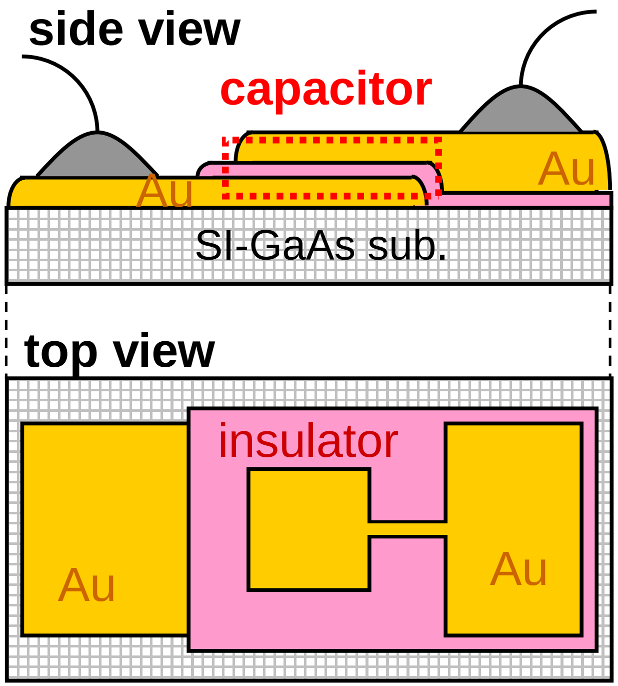
2. $T_C$ & $\Delta T_C$ of (Ga,Mn)As channels in FET

· Channel thickness dependence

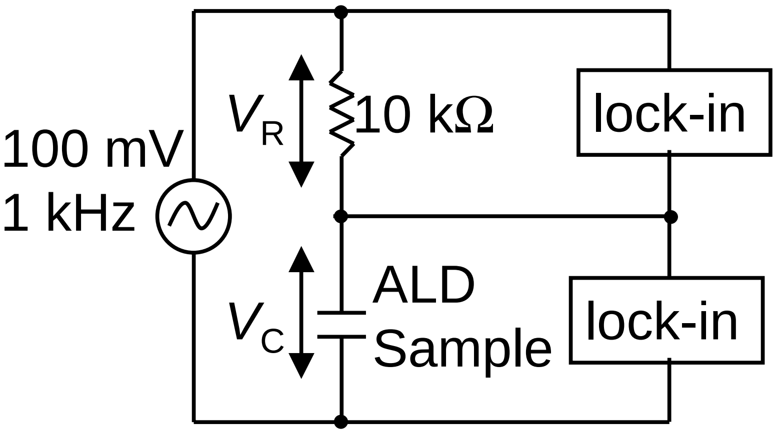
· Mn composition dependence

# Au/insulator/Au capacitors

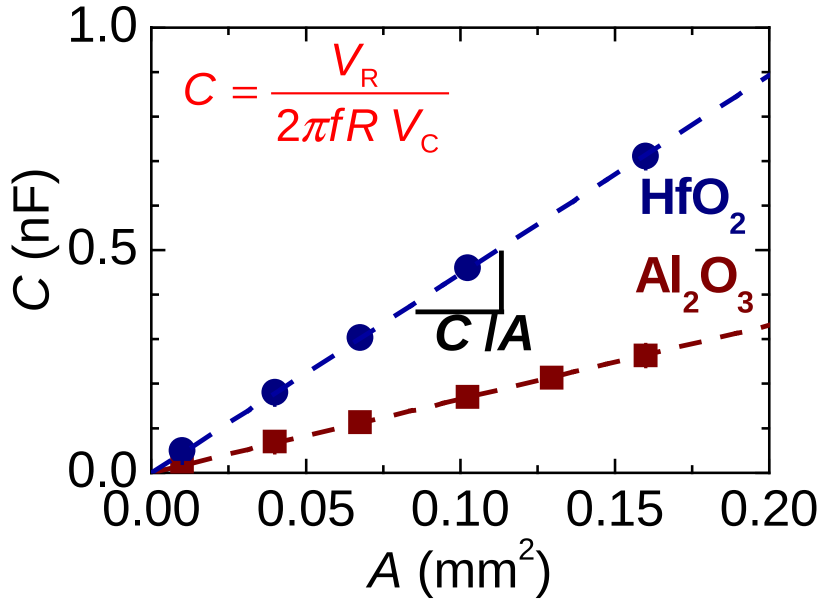
## Device structure

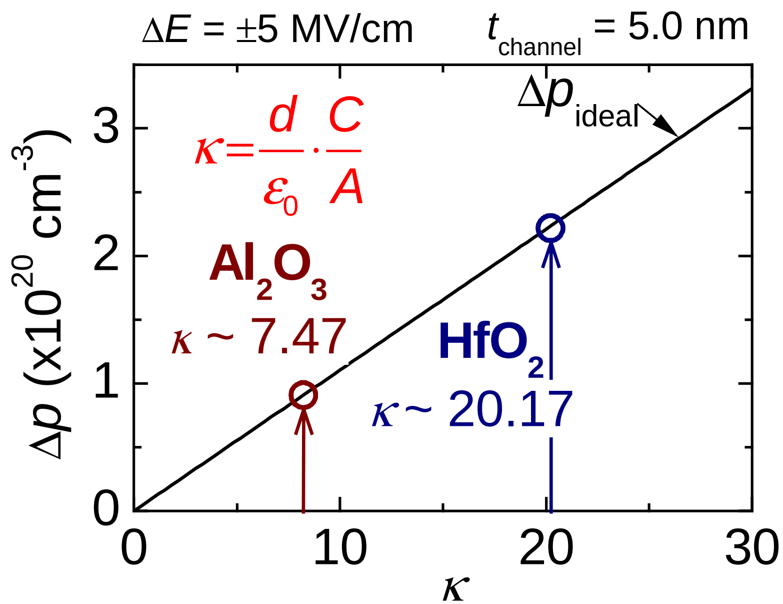



## Measurement




M. J. Biercuk *et al.* Appl. Phys. Lett. **83**, 2405 (2003).

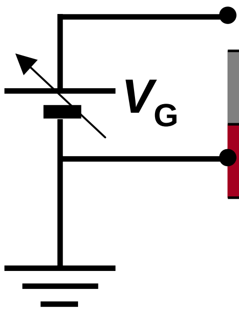



$A$: area of capacitor, $d$: thickness of insulator

# (Ga,Mn)As FETs

## typical sample structure




| | | |
|---|---|---|
| metal | 100/5 nm | Au/Cr |
| insulator | 50 or 40 nm | $Al_2O_3$ or $HfO_2$ |
| channel | 5.0 nm | $Ga_{0.949}Mn_{0.051}As$ |
| buffer | 5.0 nm | GaAs |
| | 30 nm | $Al_{0.80}Ga_{0.20}As$ |
| | 500 nm | $In_{0.15}Ga_{0.85}As$ |
| | 30 nm | GaAs |
| substrate | S.I. GaAs substrate (001) | |

Evaporation

ALD

MBE

strain induced perpendicular magnetic easy axis

consistent with the p-d Zener model

## FET fabrication

·Mesa structure with Hall bar geometry

photolithography and wet etching

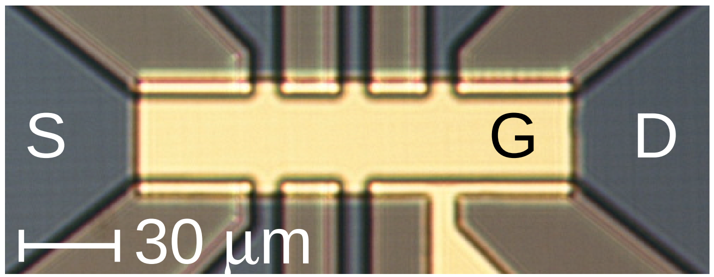
·Gate insulator

ALD

·Metal gate

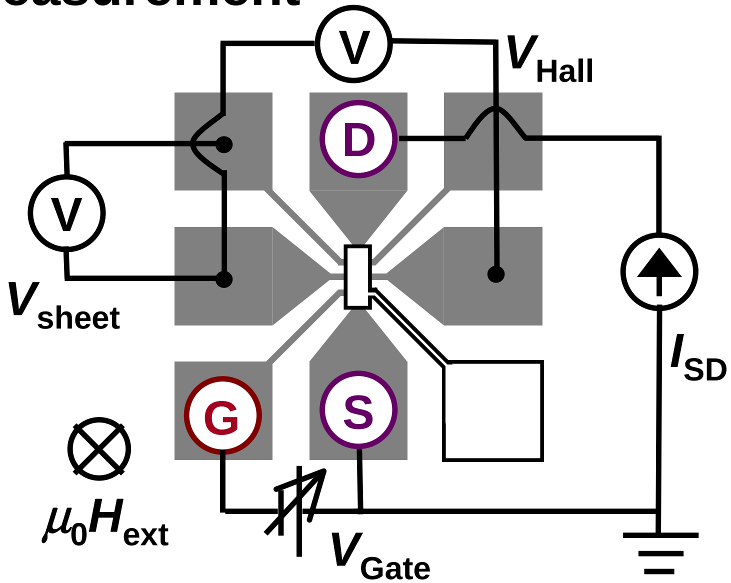
evaporation and lift-off

FET device with Hall-bar shape



# (Ga,Mn)As FETs

## Measurement




anomalous Hall effect

$$R_{Hall} = \frac{R_0}{t}\mu_0 H + \boxed{\frac{R_S}{t}M_\perp}$$

$t$: channel thickness

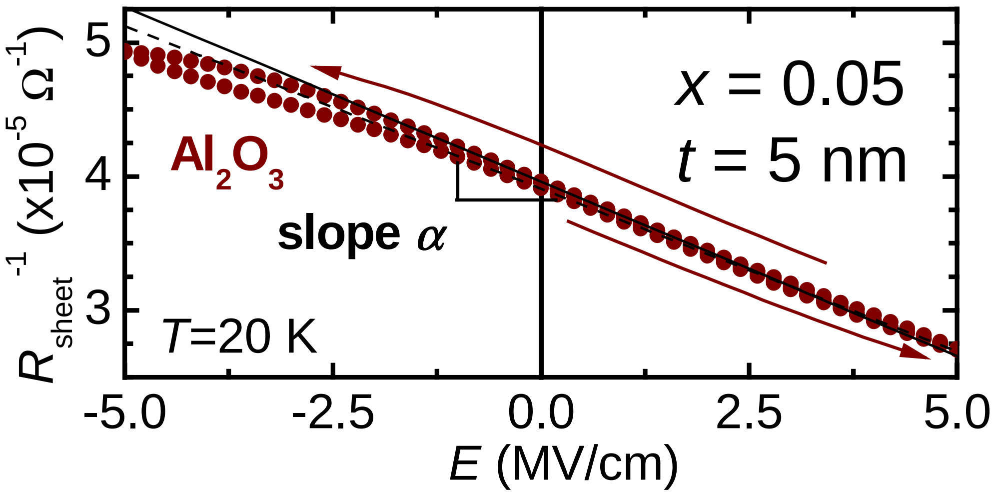
$I_{SD} = 1\ \mu A$

$T = 10 \sim 250$ K

$|\mu_0 H| \leq 0.5$ T

$|E| \leq 5$ MV/cm

## $E$ dependence of $R_{sheet}$




$$\Delta p(E) = \frac{\kappa\varepsilon_0}{et}E$$

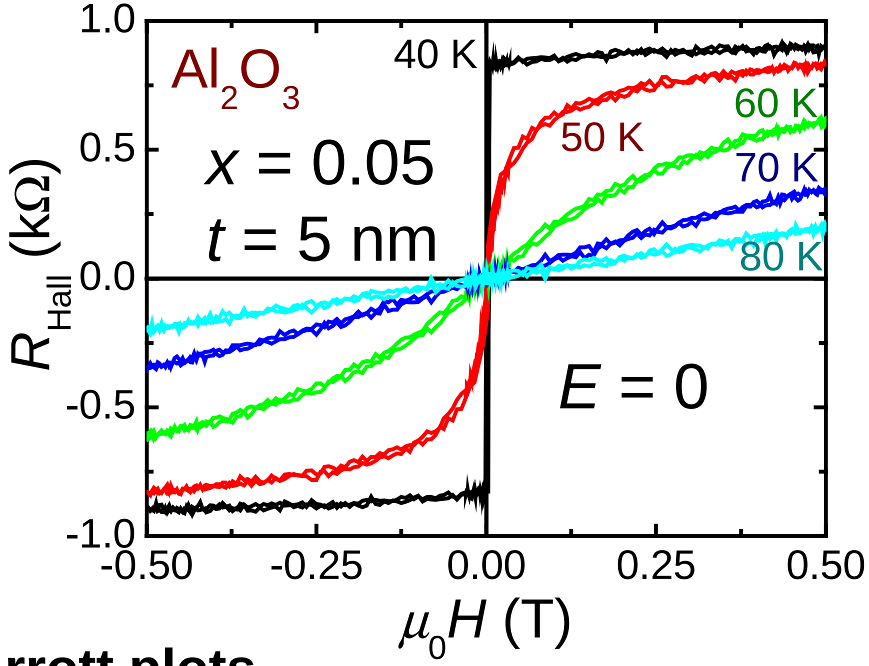
$$R_{sheet}^{-1} = \mu e t[p + \Delta p(E)] = \mu(ept - \kappa\varepsilon_0 E)$$

$$\mu = -\frac{\alpha}{\varepsilon_0 \kappa}$$

$$p(E) = \frac{1}{\mu e t}\frac{1}{R_{sheet}(E)}$$

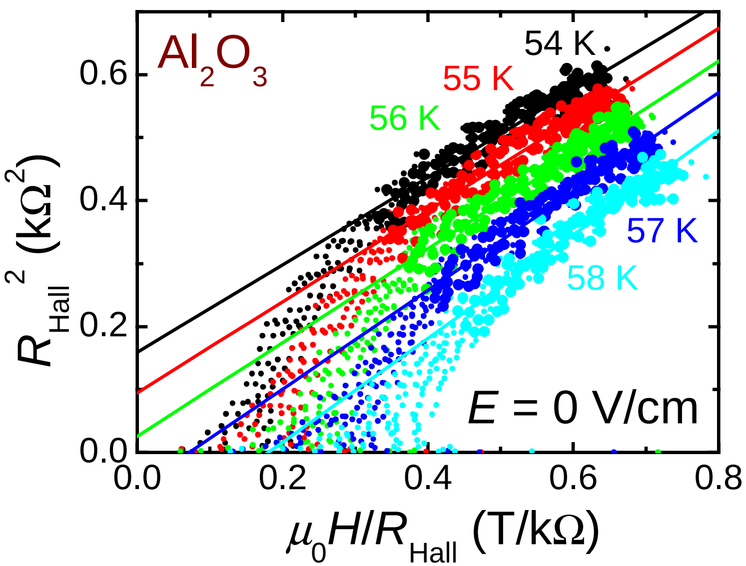
# (Ga,Mn)As FET

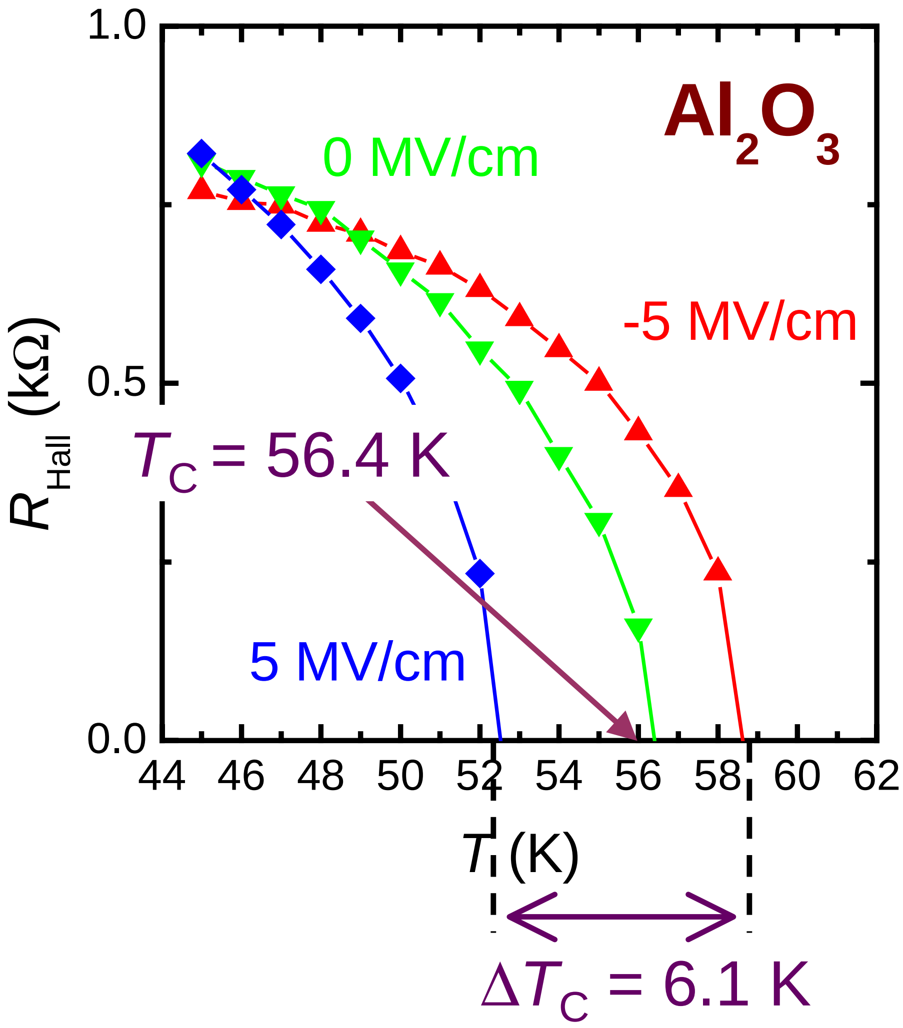
## Magnetotransport properties




$$R_{\mathrm{Hall}} = \frac{R_0}{t}\mu_0 H + \frac{R_S}{t} M_\perp$$

**Arrott plots**



# channel thickness dependence

# (Ga,Mn)As FETs with different channel thickness

**Sample structure**

| | | |
|---|---|---|
| metal | 100/5 nm | Au/Cr |
| insulator | 40 nm | $Al_2O_3$ |
| channel | *t* nm | $Ga_{0.935}Mn_{0.065}As$ |
| buffer | 5.0 nm | GaAs |
| | 30 nm | $Al_{0.75}Ga_{0.25}As$ |
| | 500 nm | $In_{0.15}Ga_{0.85}As$ |
| | 30 nm | GaAs |
| substrate | S.I. GaAs substrate (001) | |

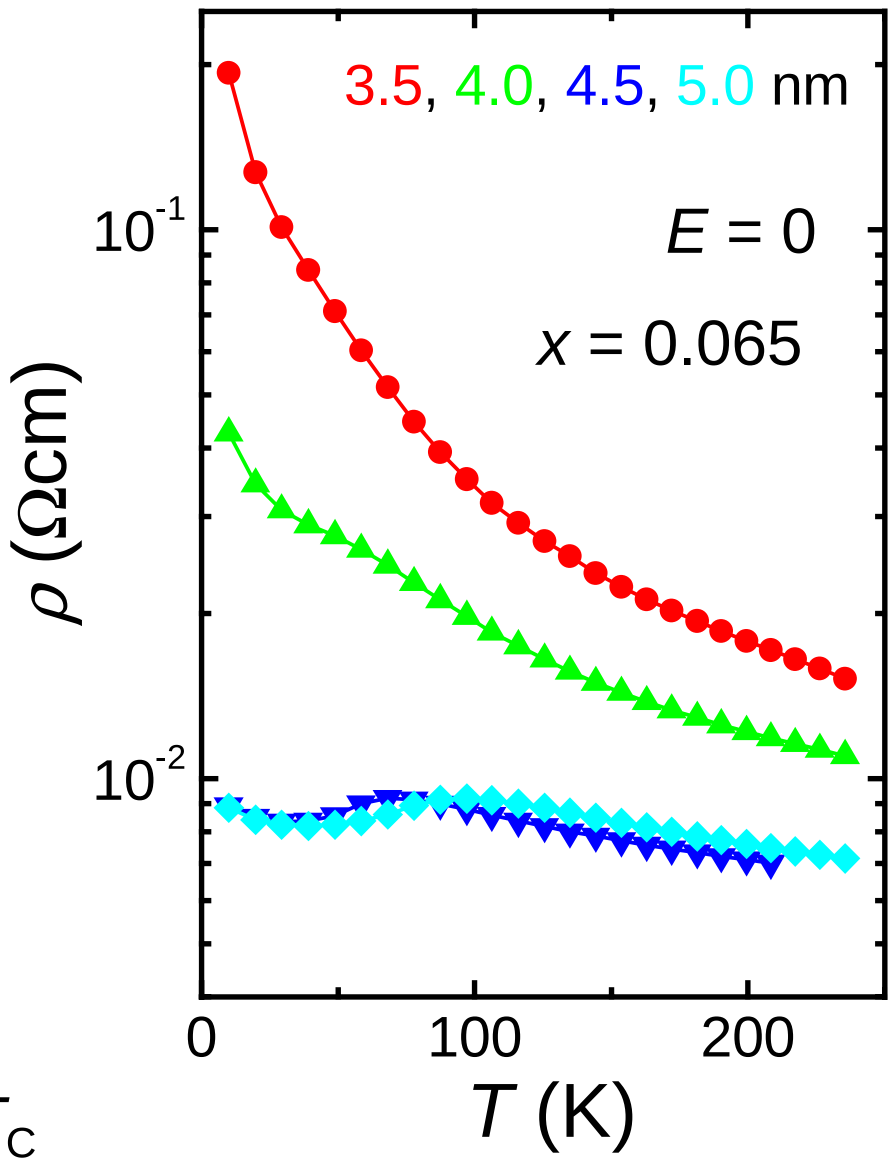
$t$ = 3.5, 4.0, 4.5, and 5.0 nm

insulating (3.5, 4.0) metallic (4.5, 5.0)

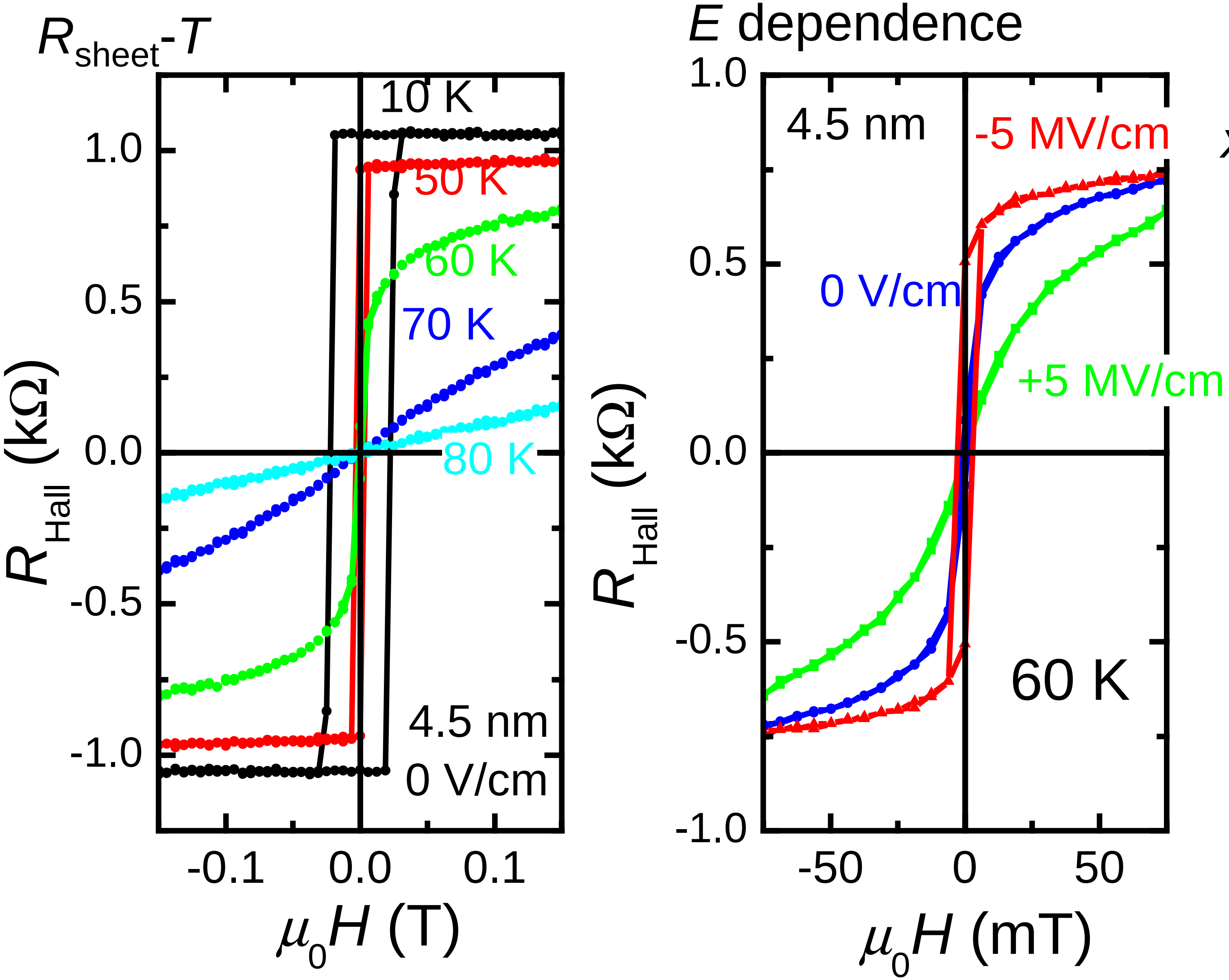
$$\Delta p(E) = \frac{\kappa\varepsilon_0}{et}E$$

$\Delta p$ for thinner layer → larger $\Delta T_C$

**$R_{sheet}$-$T$**

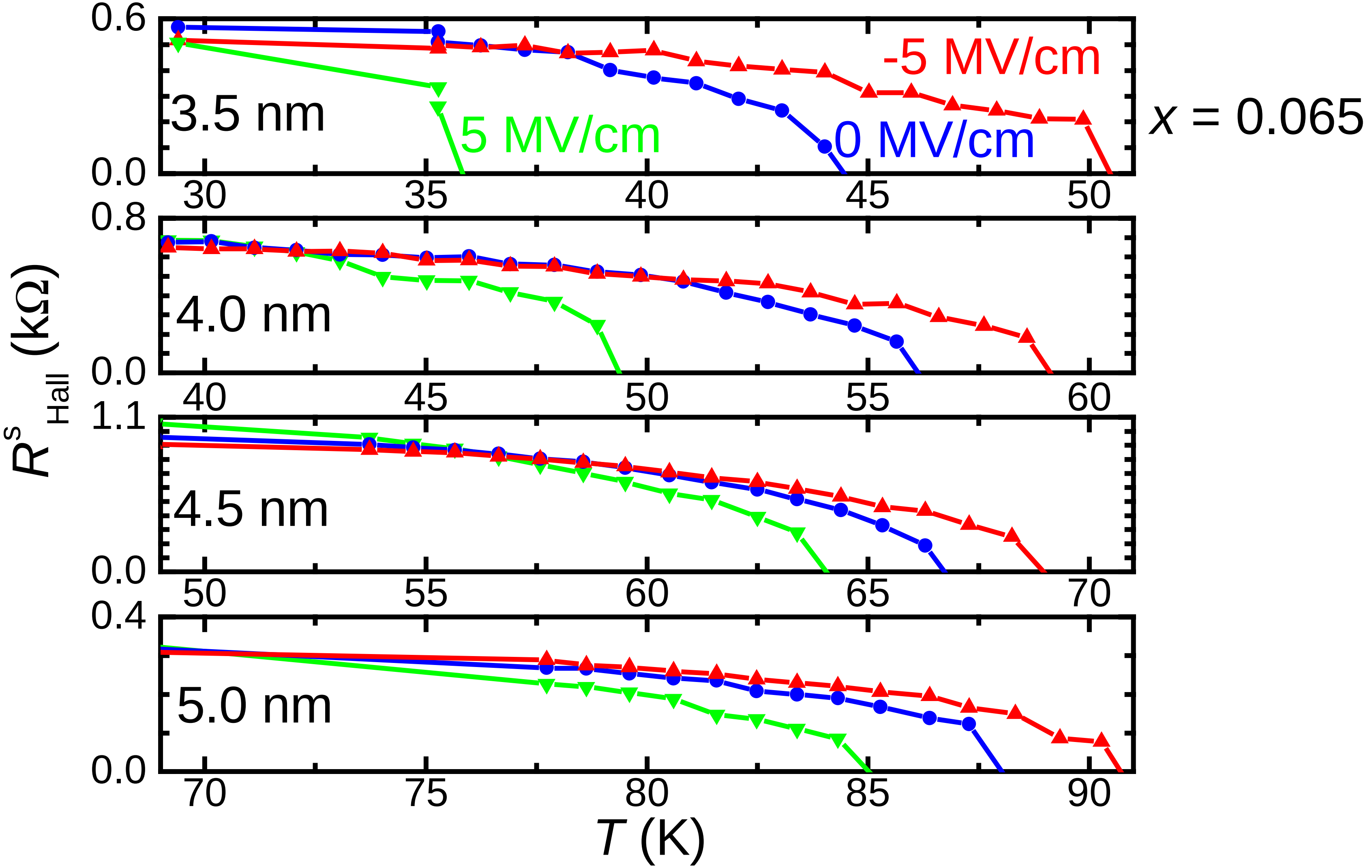


**(Ga,Mn)As FETs with different channel thickness**
**Typical results**



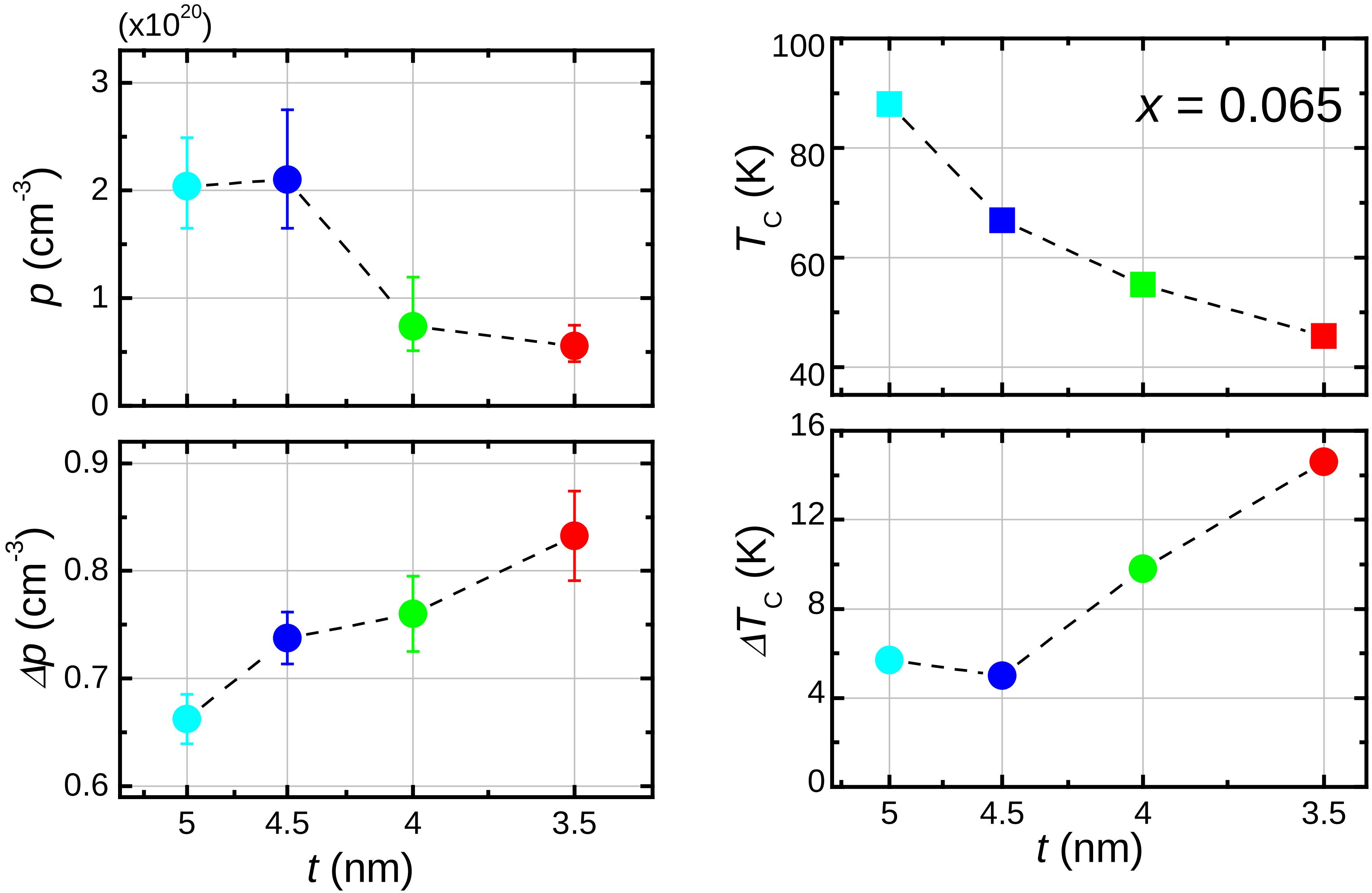

$x = 0.065$

## (Ga,Mn)As FETs with different channel thickness
## Curie temperature




larger $T_C$ and smaller $\Delta T_C$ for thicker chnnael

## (Ga,Mn)As FETs with different channel thickness
## Hole concentration & Curie temperature

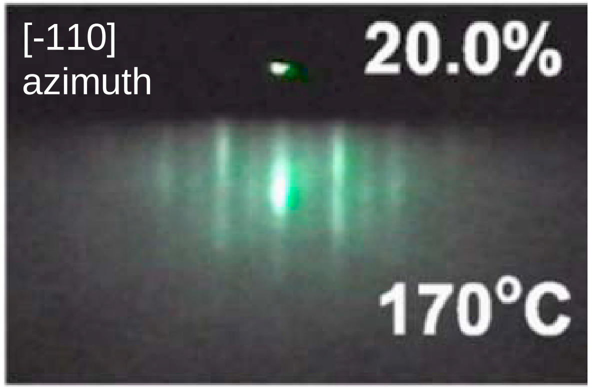



FETs with thinner channel have larger $\Delta T_C$ as well as $\Delta p$

# Mn composition dependence

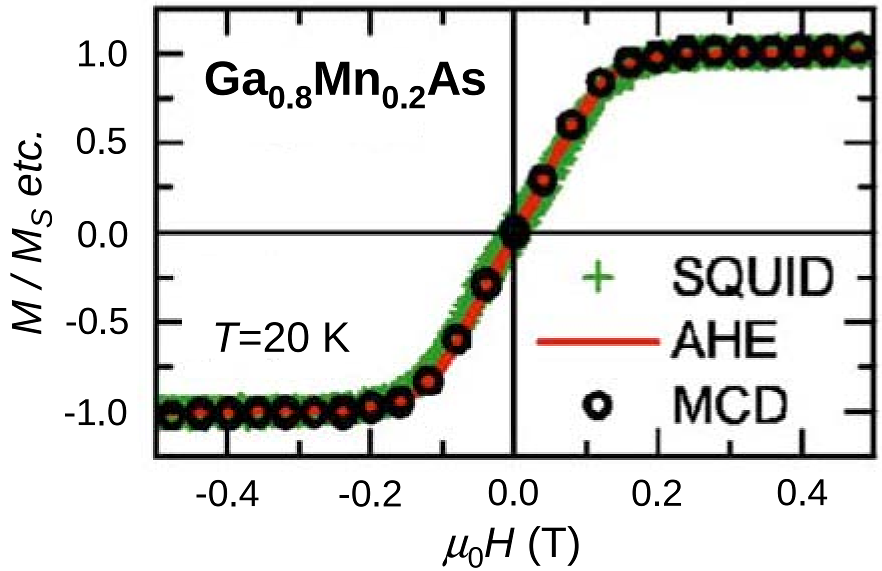
# Growth of $Ga_{1-x}Mn_xAs$ with High $x$ (~ 0.2 )

| Channel layer | 5 nm | $Ga_{0.8}Mn_{0.2}As$ |
|---|---|---|
| Buffer layer | 4 nm | GaAs |
| | 30 nm | $Al_{0.75}Ga_{0.25}As$ |
| | 420 nm | $In_{0.15}Ga_{0.85}As$ |
| | 30 nm | GaAs |
| Substrate | S.I. GaAs (001) sub. | |




✓ decrease $T_S$

✓ thinner layer

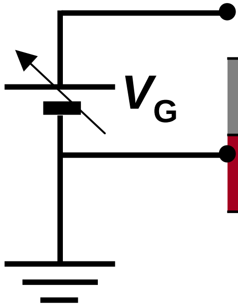



**Single phase $Ga_{1-x}Mn_xAs$ with higher x**

D.Chiba *et al*., Appl. Phys. Lett. **90**, 122503 (2007).

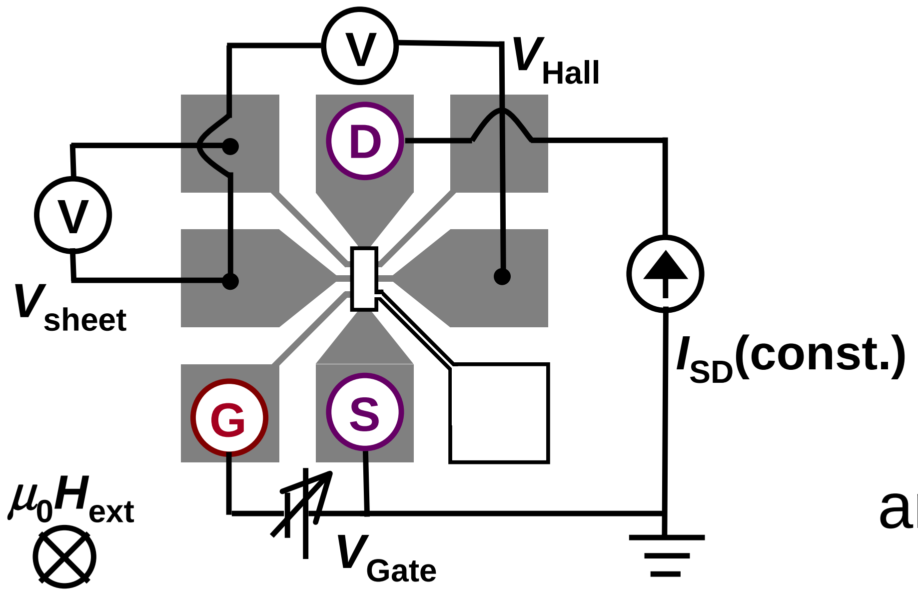
S. Ohya *et al*., Appl. Phys. Lett. **90**, 112503 (2007).

# (Ga,Mn)As FETs with various Mn compositions



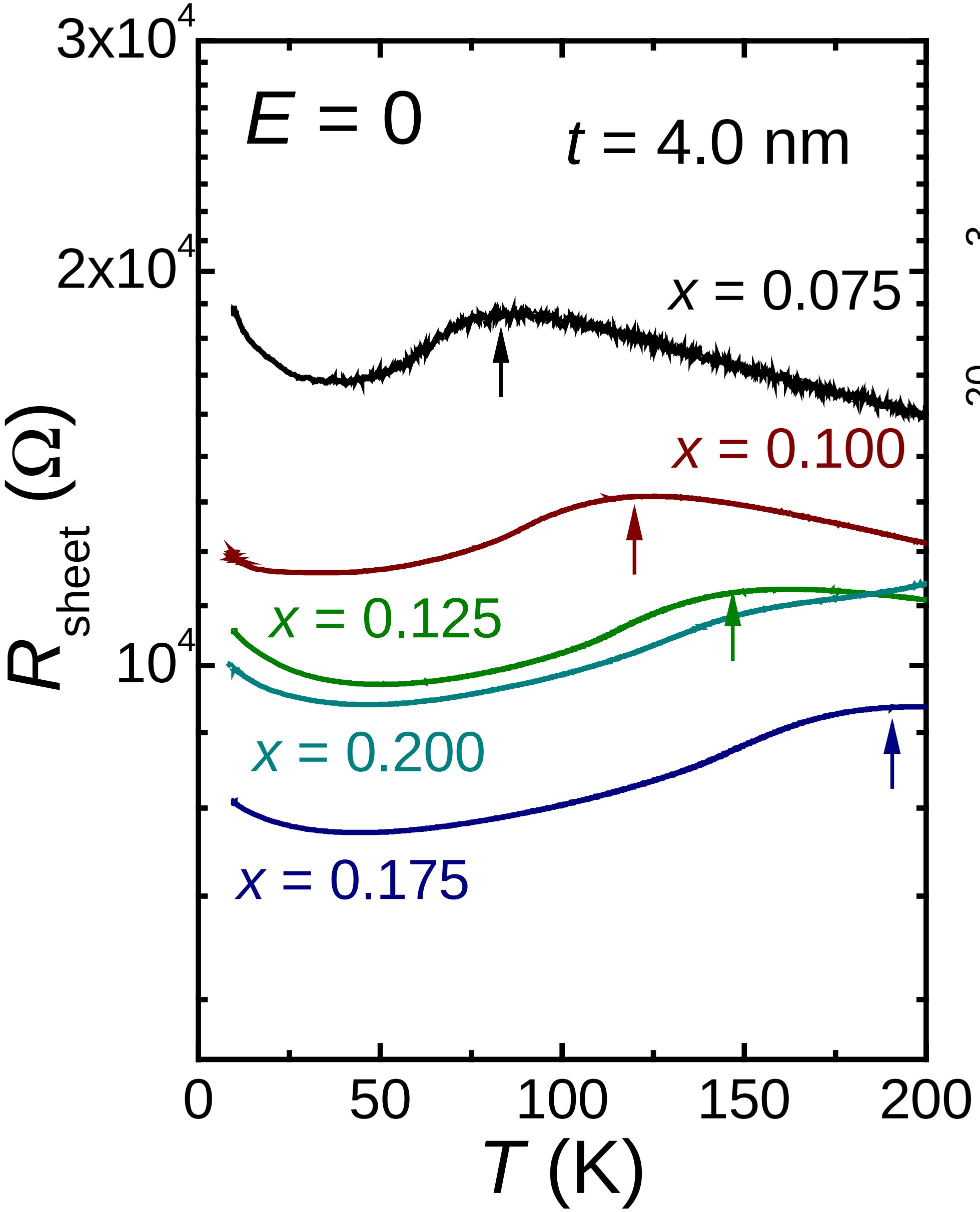

| | | | |
|---|---|---|---|
| Gate electrode | 100 nm | Cr / Au | evaporation |
| Gate insulator | 40 nm | $HfO_2$ | ALD |
| Channel layer | 4.0 nm | $Ga_{1-x}Mn_xAs$ | MBE |
| Buffer layer | 4.0 nm | GaAs | |
| | 30 nm | $Al_{0.75}Ga_{0.25}As$ | |
| | 420 nm | $In_{0.15}Ga_{0.85}As$ | |
| | 30 nm | GaAs | |
| Substrate | S. I. GaAs substrate (001) | | |

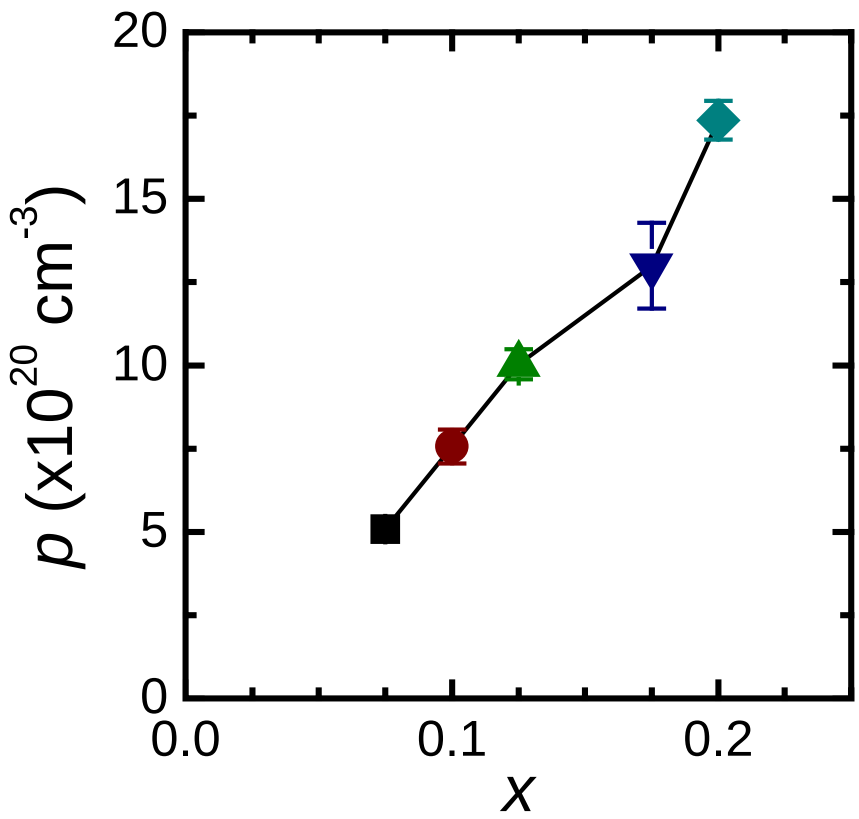
$x =$ 0.075, 0.100, 0.125, 0.175, 0.200




annealed at 180°C for 5 min

# (Ga,Mn)As FETs with various Mn compositions

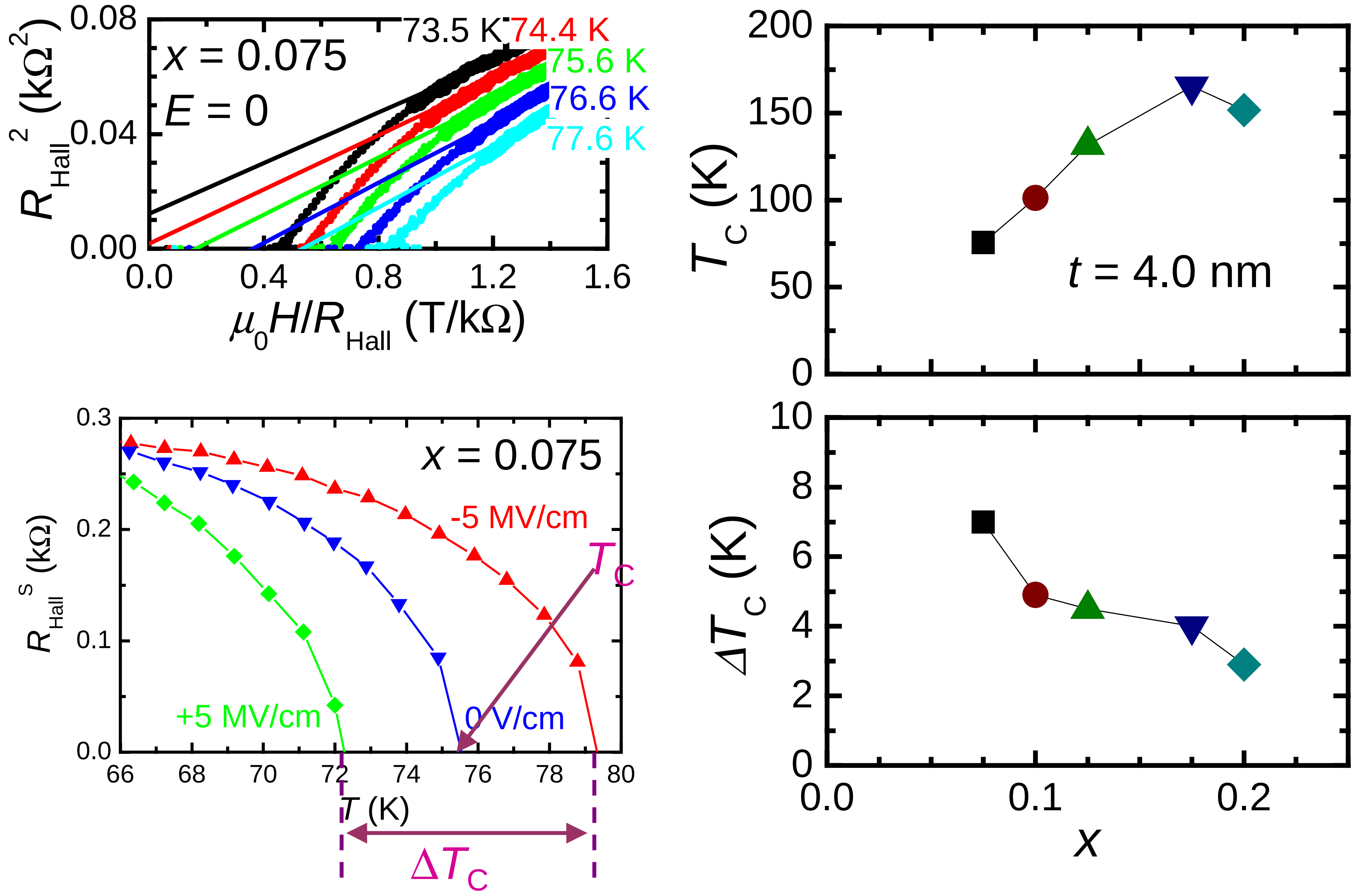



higher $x \rightarrow$ higher $p$

$> 10^{21}$ cm$^{-3}$

# (Ga,Mn)As FETs with various Mn compositions



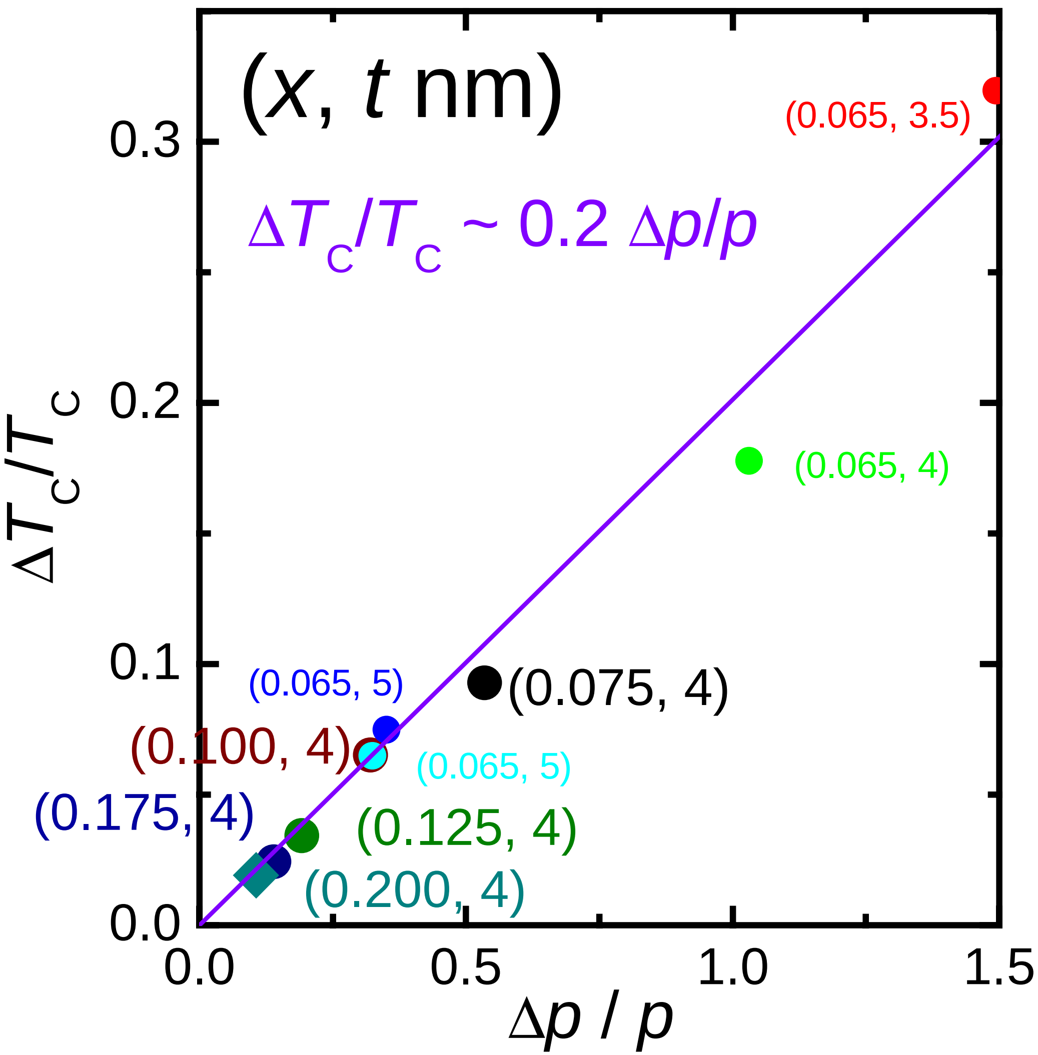
## Summary of experimental results

**(Ga,Mn)As channel itself**

- larger $T_C$ and $p$ for thicker channel and higher $x$

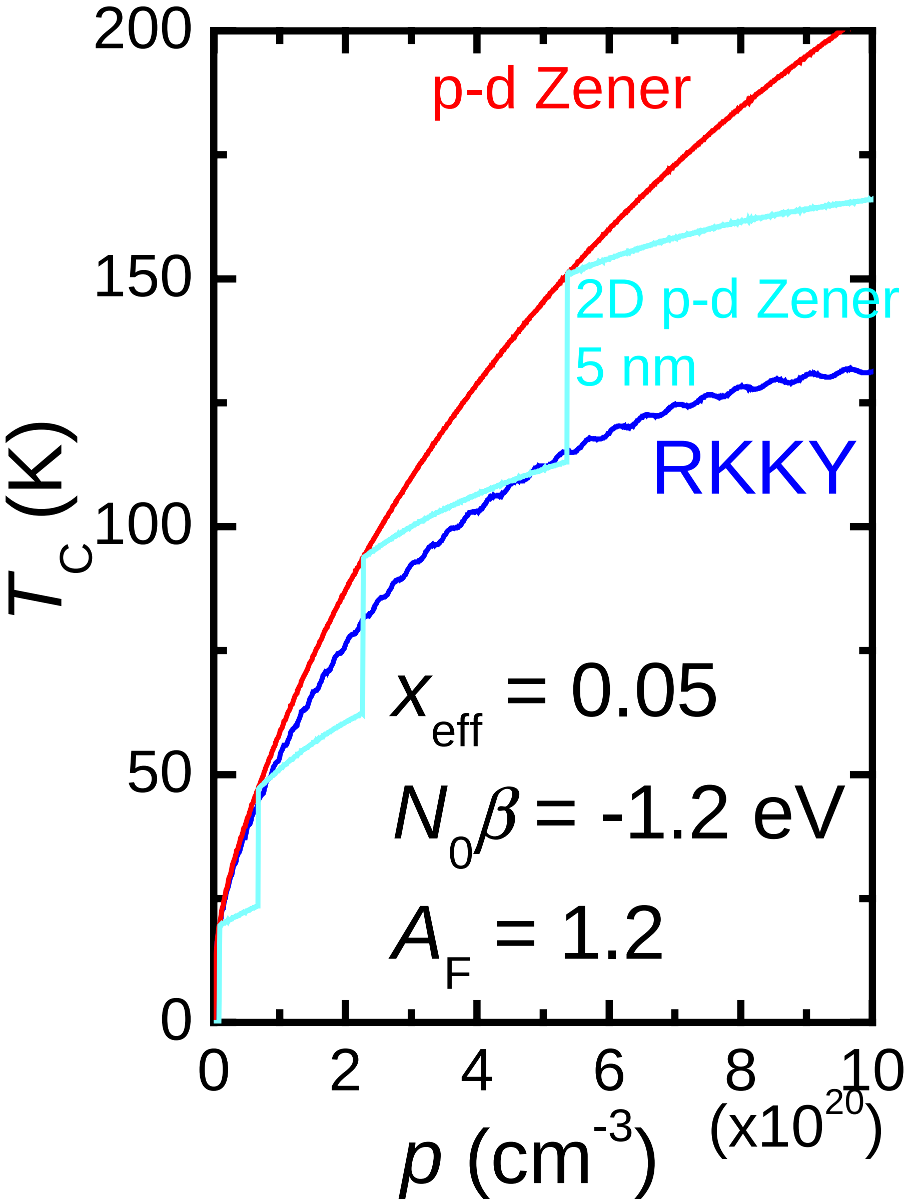
**(Ga,Mn)As channel in FET**

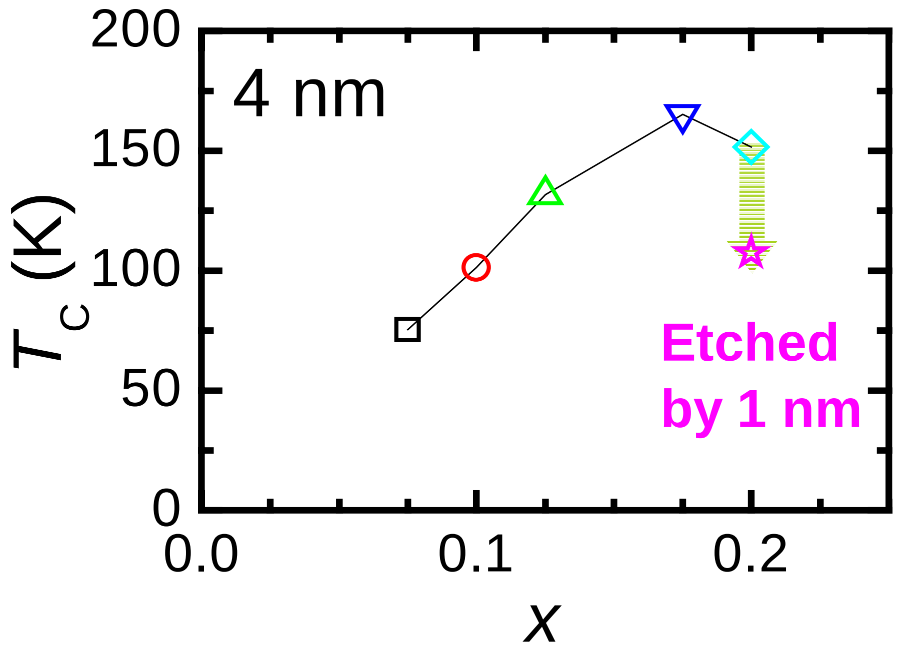
- larger $\Delta T_C$ for thinner channel and smaller $x$




$\Delta T_C/T_C \sim 0.6 \Delta p/p$ is expected from the p-d Zener model

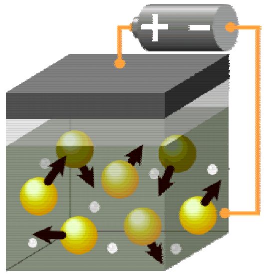
## Other effects?




- two-dimensional effect
- RKKY oscillation
- nonuniformity along growth direction
- ……

# Summary




FETs with a (Ga,Mn)As channel

· Control of $T_C$ is indeed possible by gating

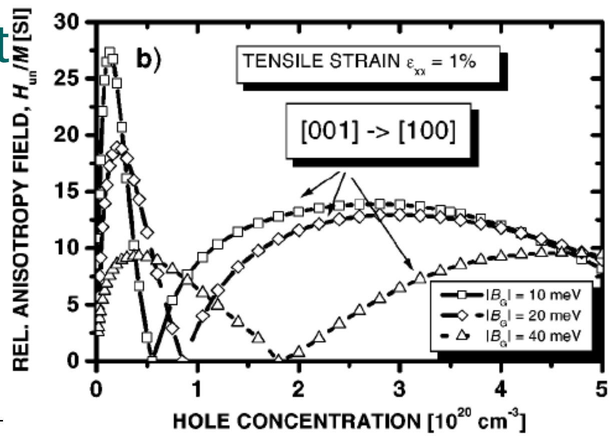
· Larger $\Delta p/p$ results in larger $\Delta T_C/T_C$; $\Delta T_C/T_C \sim 0.2\Delta p/p$

· Quantitative description ?

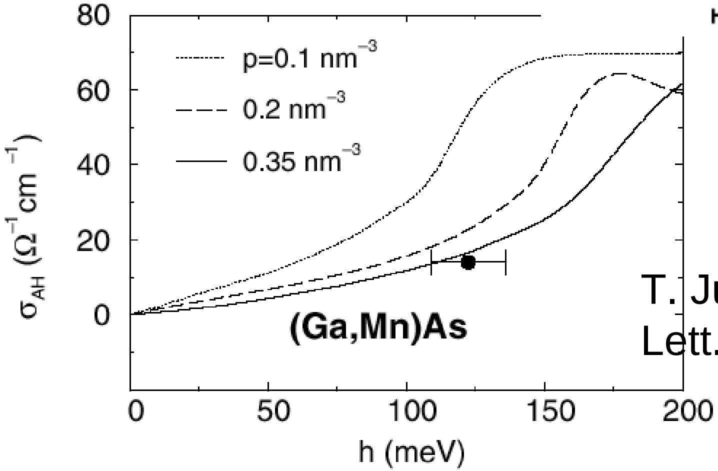
magnetization, channeling, distribution of Mn *etc*.

predicted *p* dependent properties

magnetic anisotropy




T. Dietl *et al*., Phys. Rev. B **63**, 195205 (2001).




anomalous Hall effect

T. Jungwirth *et al*., Phys. Rev. Lett. **88**, 207208 (2002).