

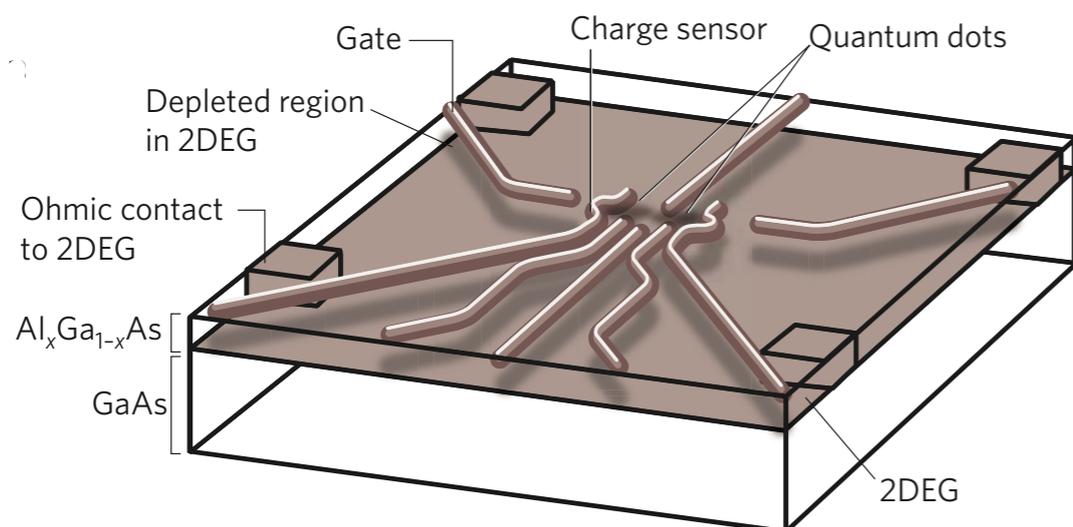
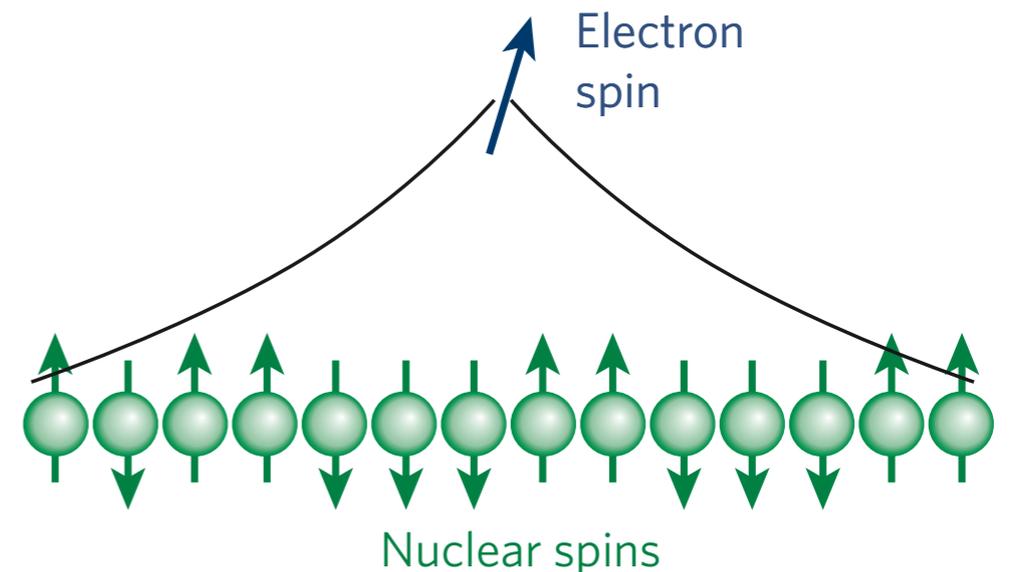
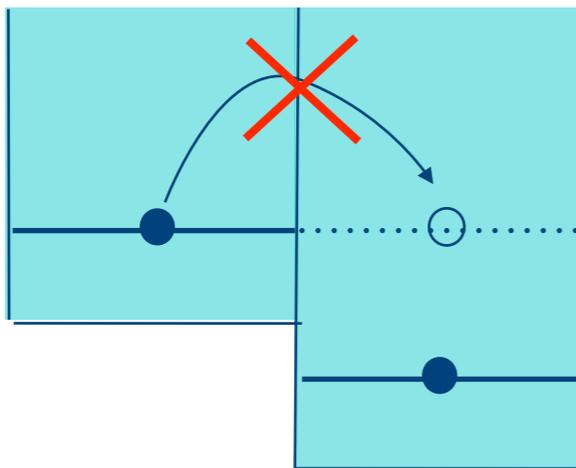
# Spin qubits szilárdtestekben

(Spinblokádkettős kvantumdotokban)

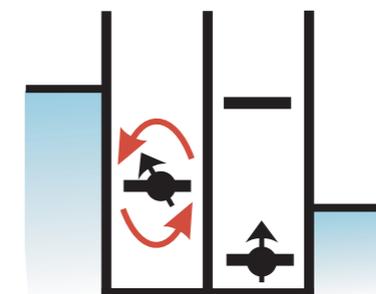
Pályi András

(1) Department of Physics, University of Konstanz, Németország

(2) Anyagfizikai Tanszék, Fizikai Intézet, ELTE



## Spin manipulation

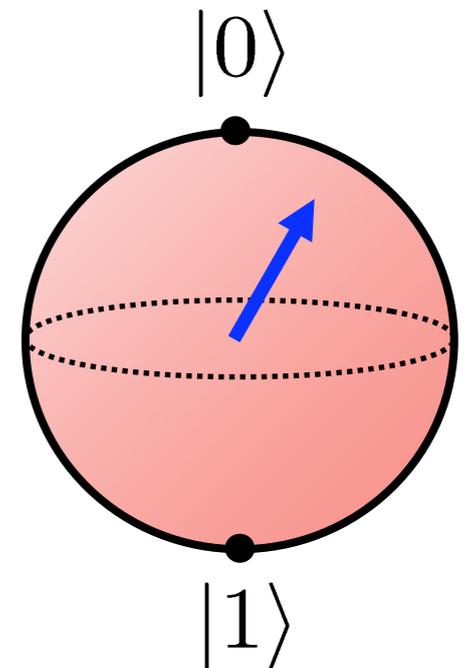


# Bevezetés - spin qubitek szilárdtestekben

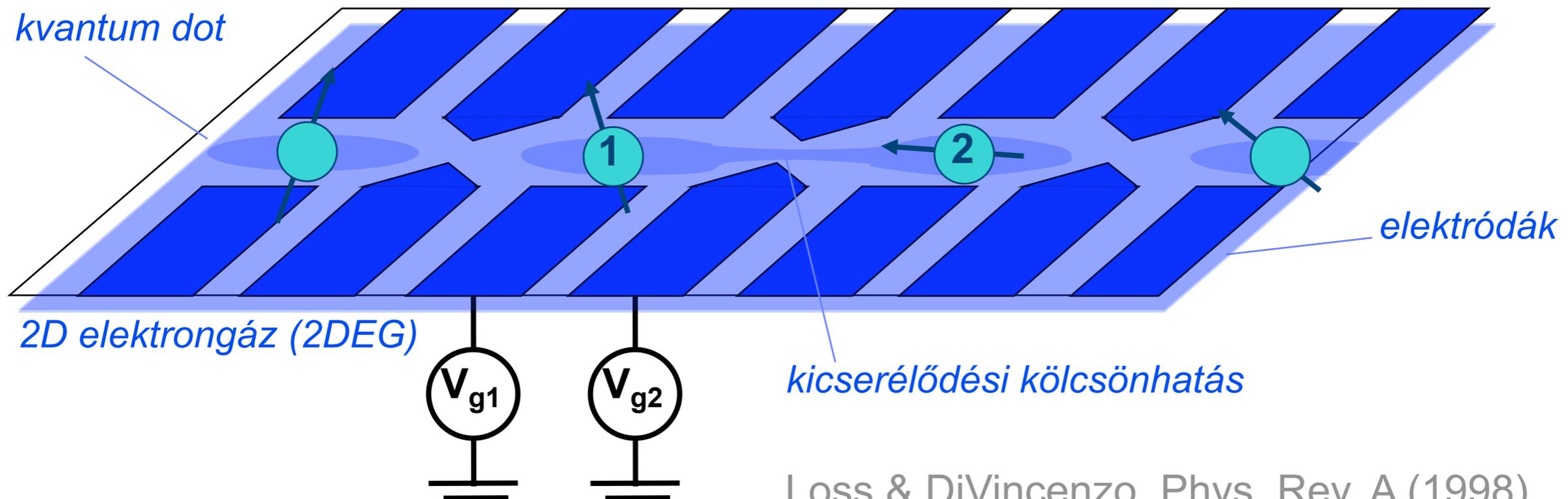
- **qubit**  $\Psi = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$   $|\alpha|^2 + |\beta|^2 = 1$

- elektron: feles spin: **spin qubit**

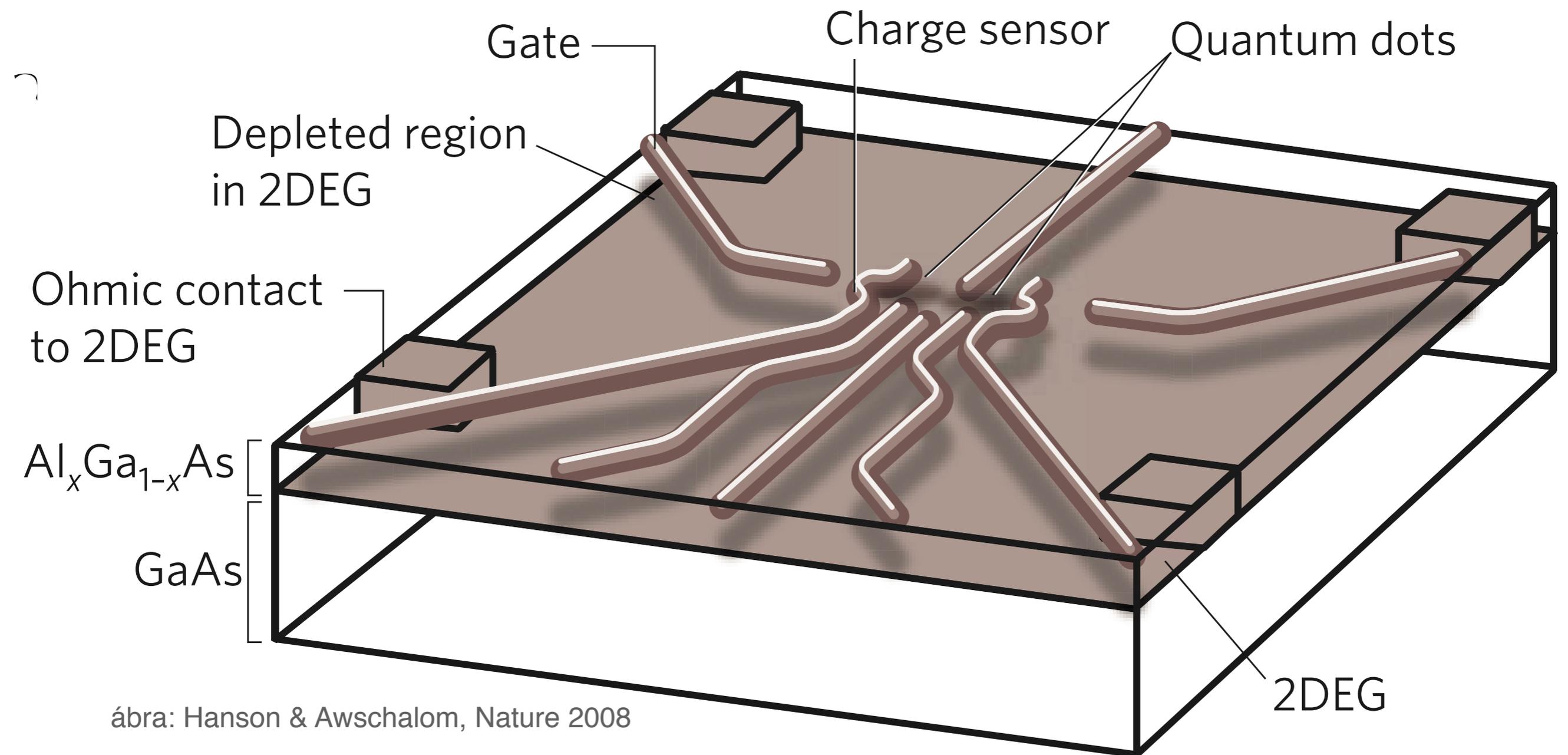
$$|0\rangle = \uparrow \quad |1\rangle = \downarrow$$



- kvantum dot: elektroncsapda, kicserélődési kcsh

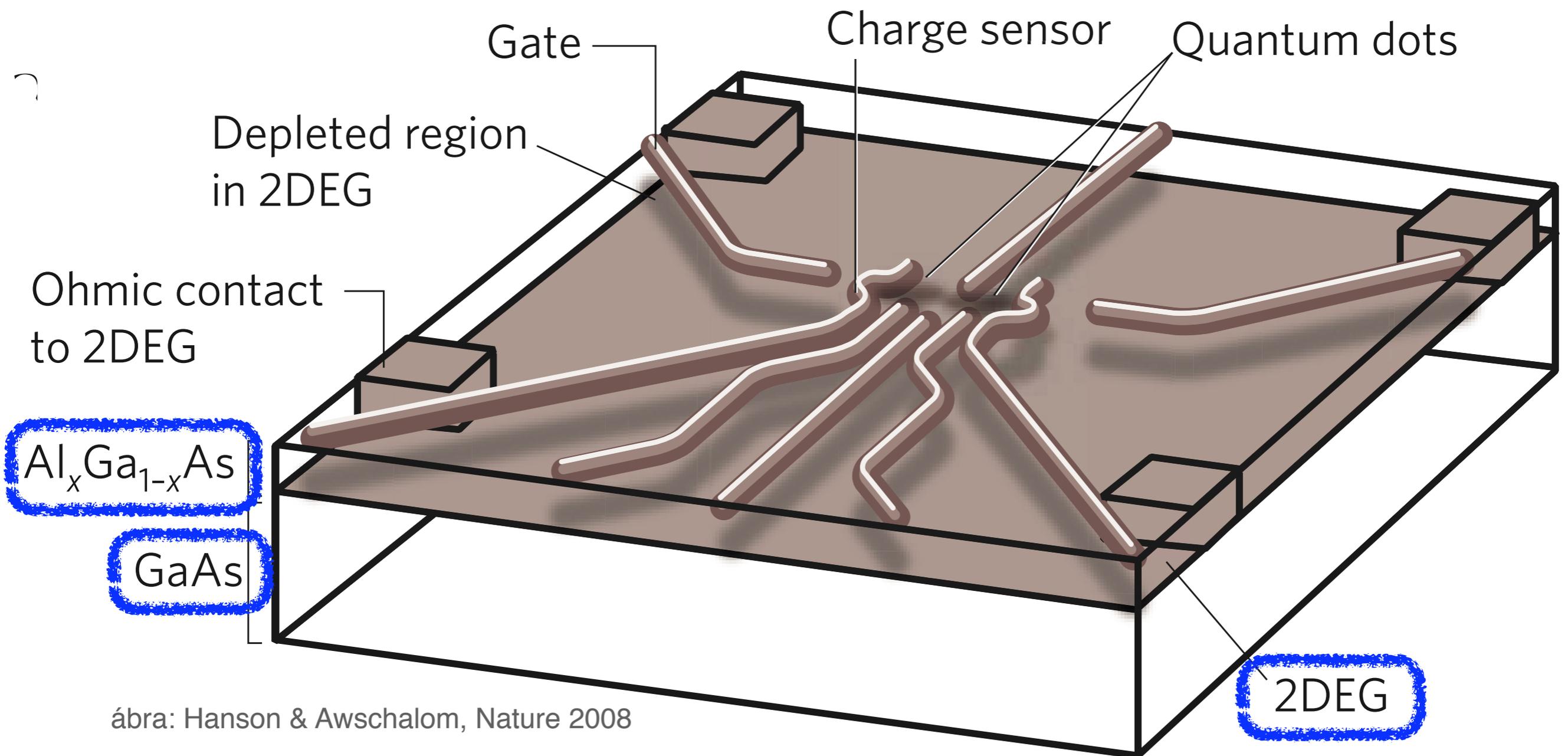


# Bevezetés - kettős kvantumdotok

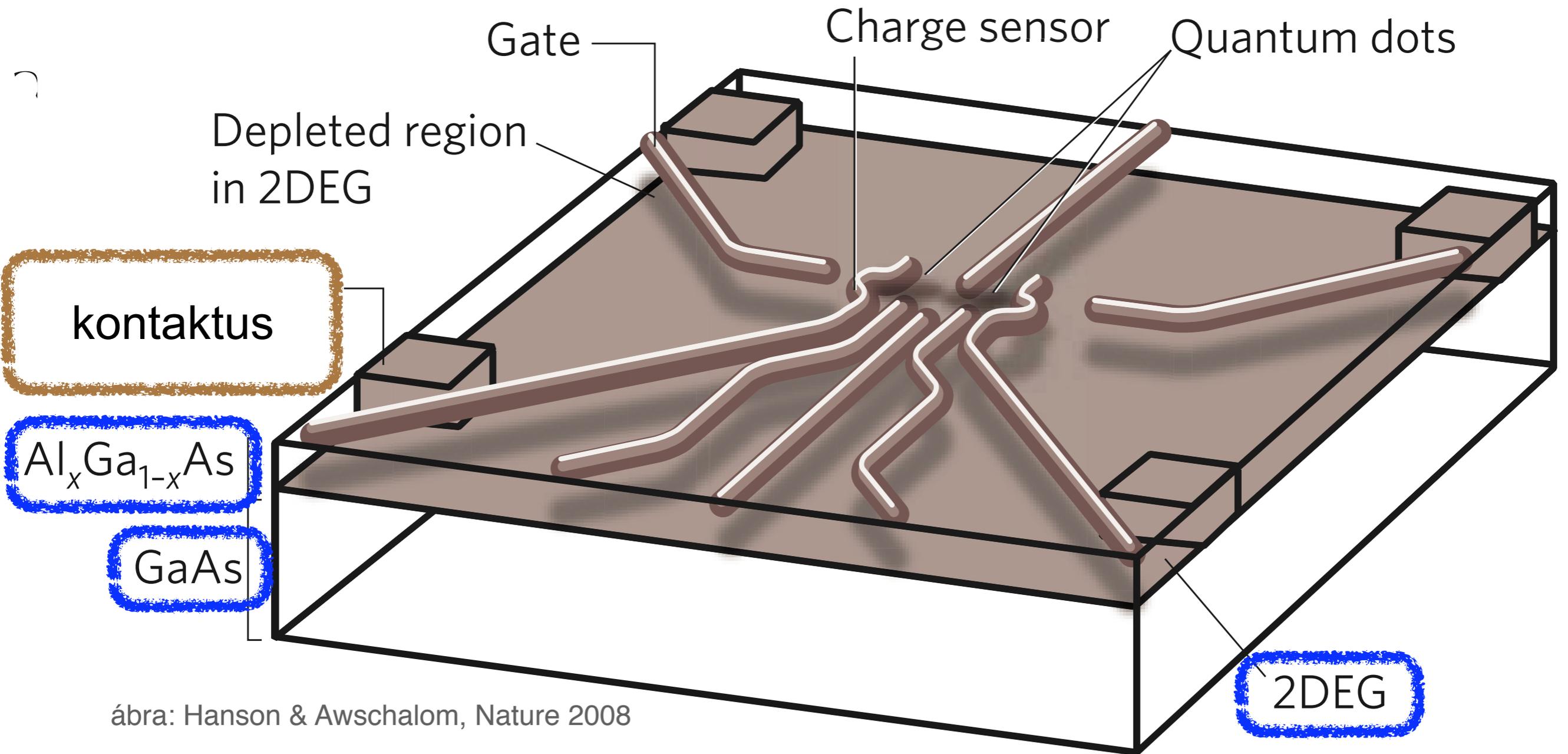


ábra: Hanson & Awschalom, Nature 2008

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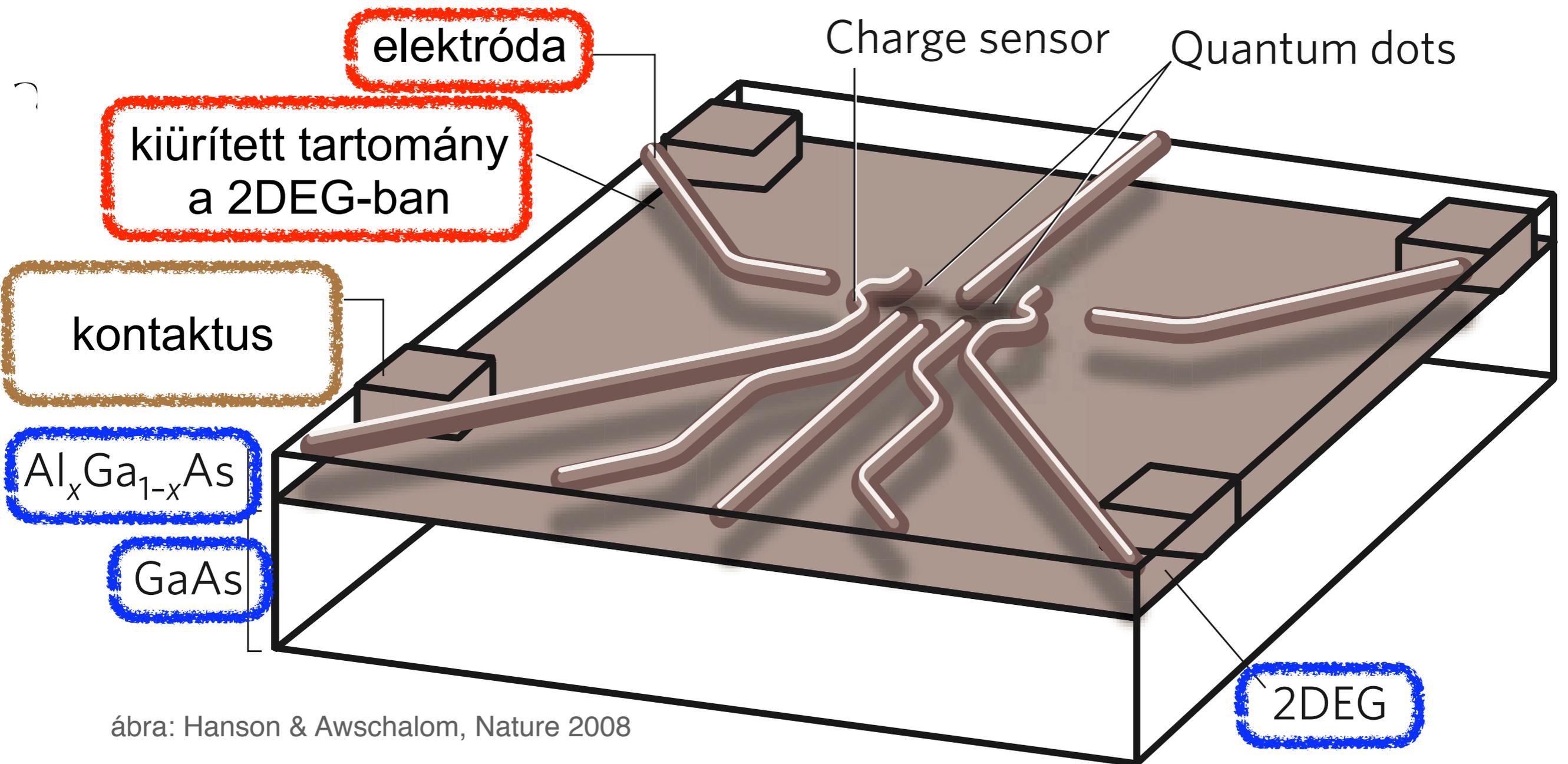


# Bevezetés - kettős kvantumdotok



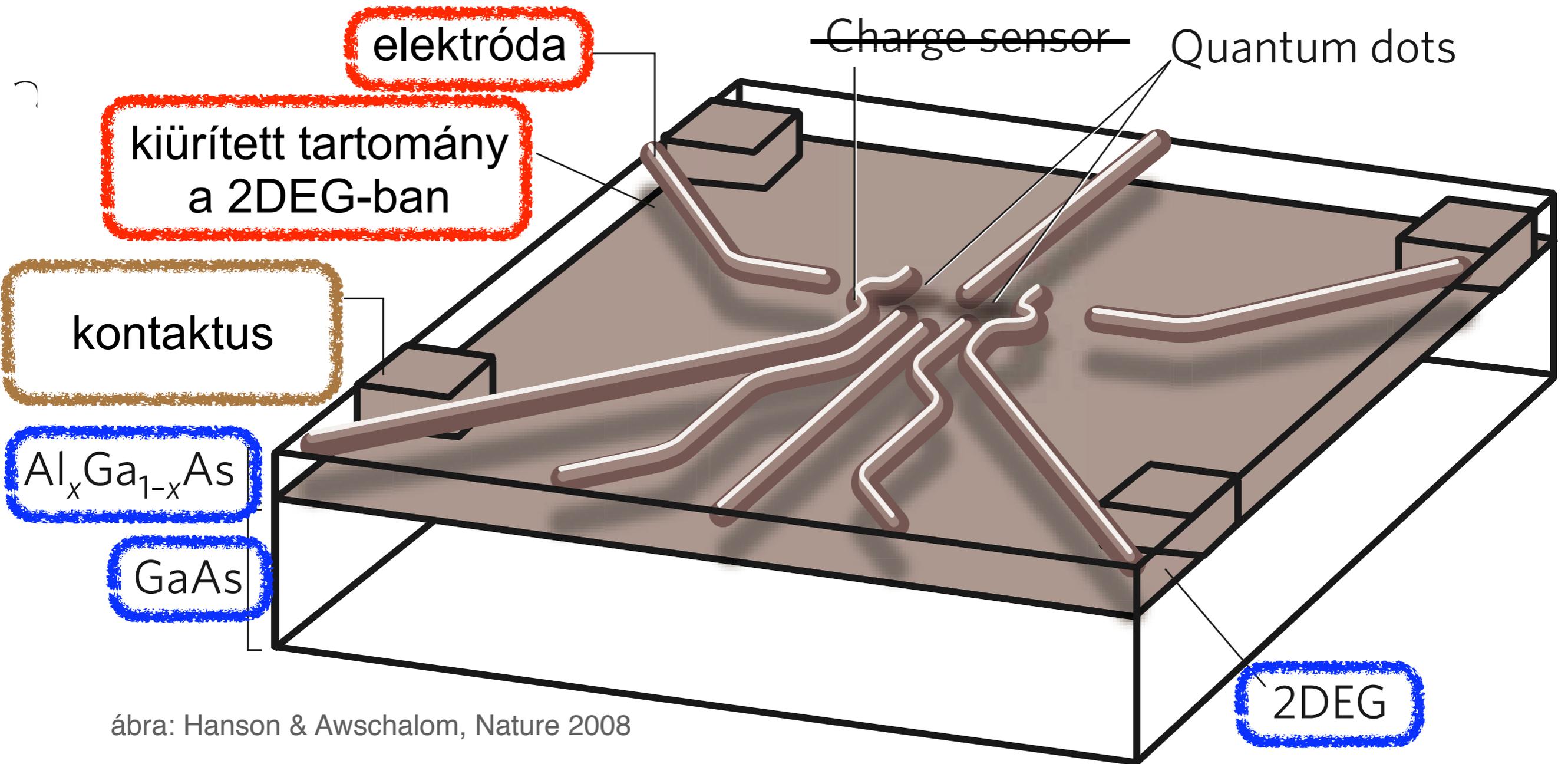
ábra: Hanson & Awschalom, Nature 2008

# Bevezetés - kettős kvantumdotok



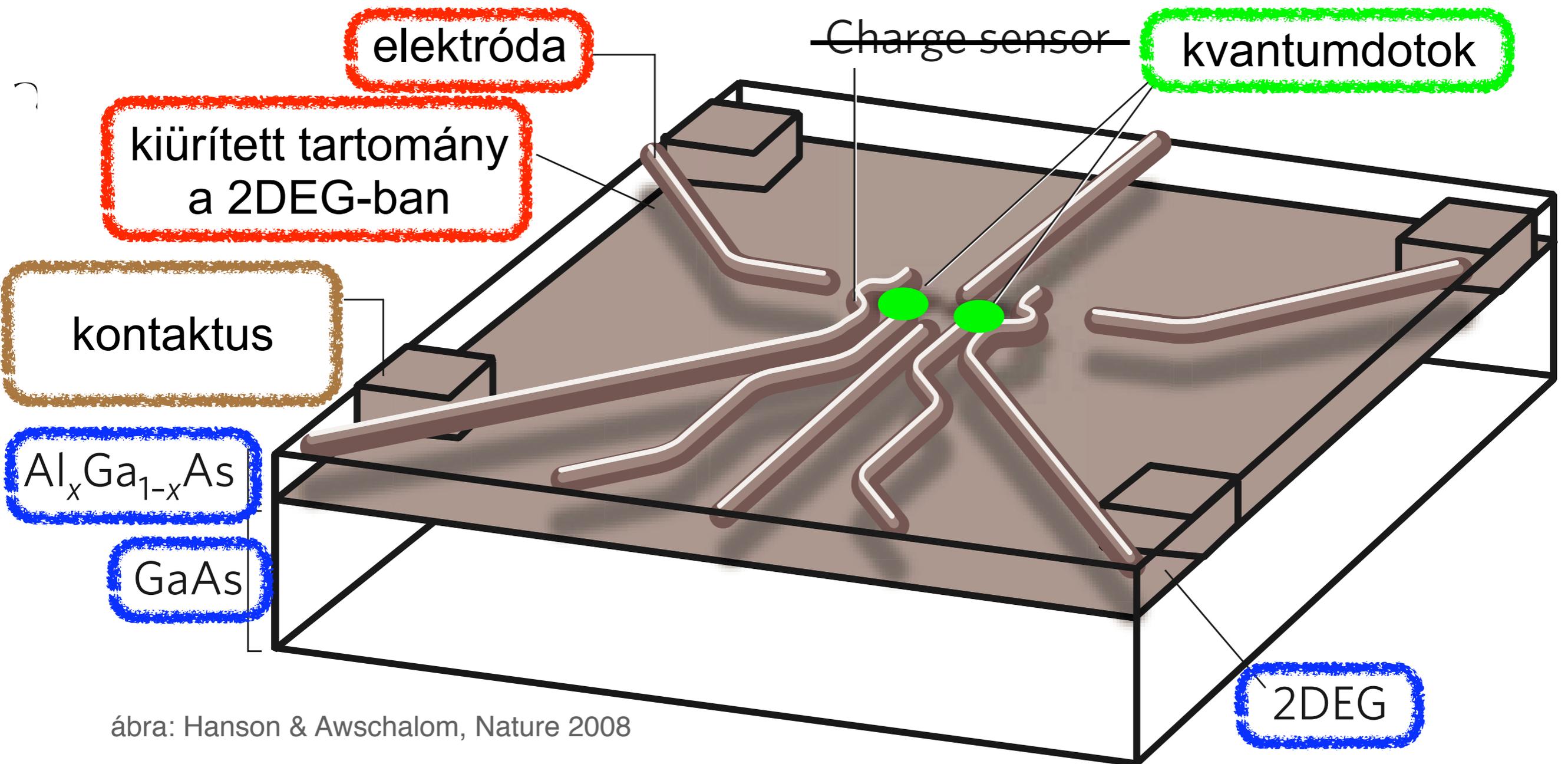
ábra: Hanson & Awschalom, Nature 2008

# Bevezetés - kettős kvantumdotok



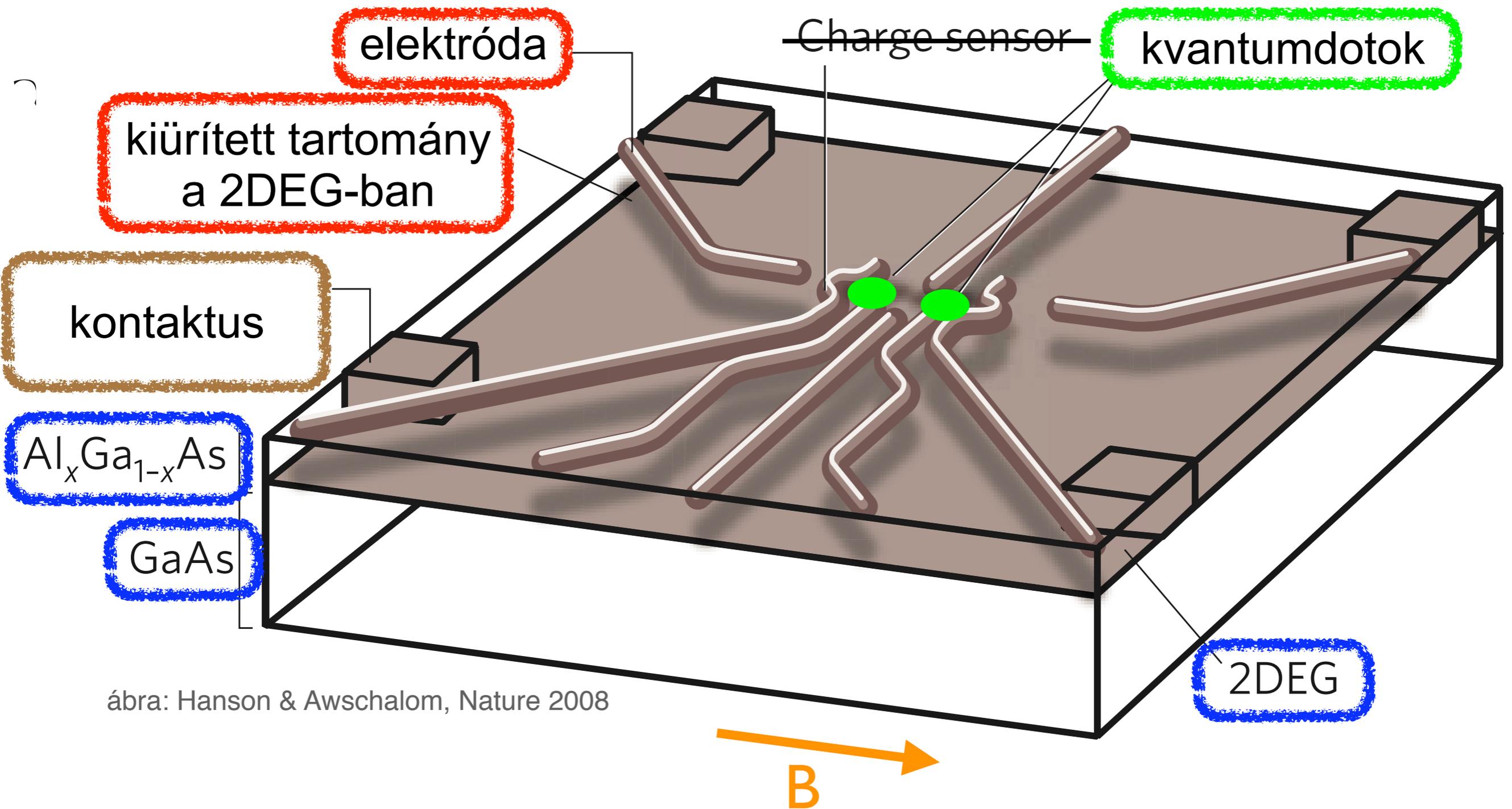
ábra: Hanson & Awschalom, Nature 2008

# Bevezetés - kettős kvantumdotok



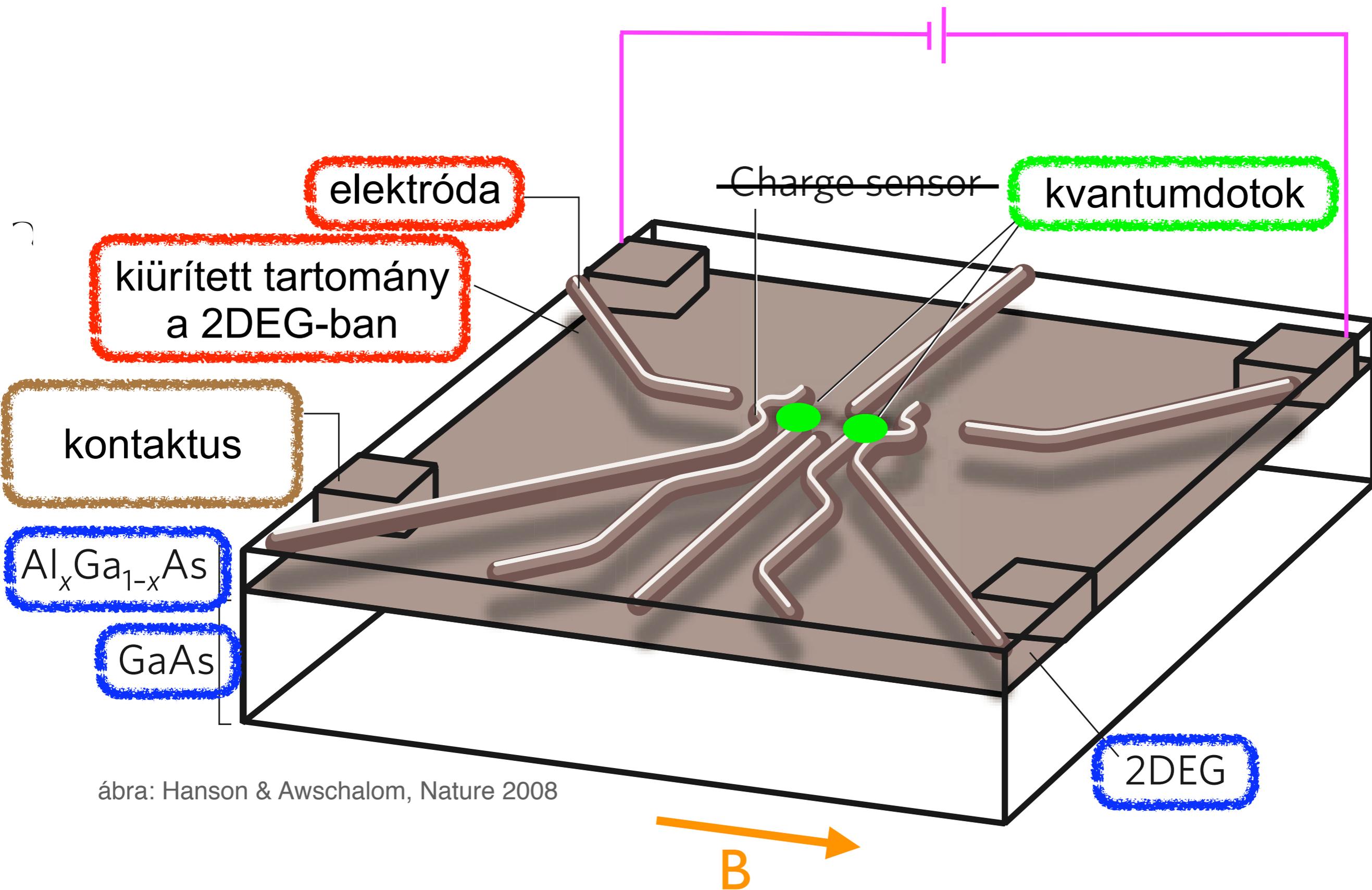
ábra: Hanson & Awschalom, Nature 2008

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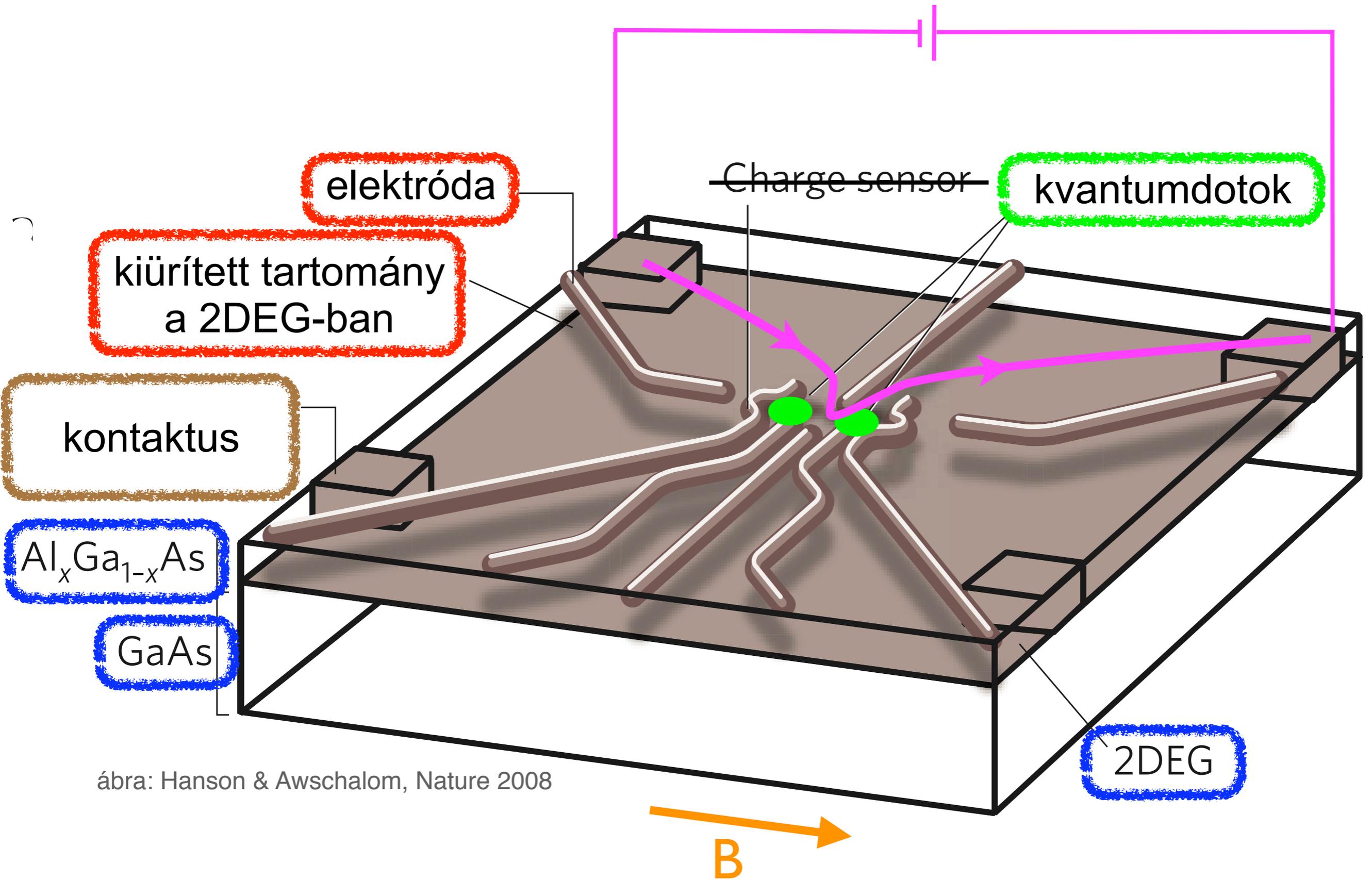
ábra: Hanson & Awschalom, Nature 2008

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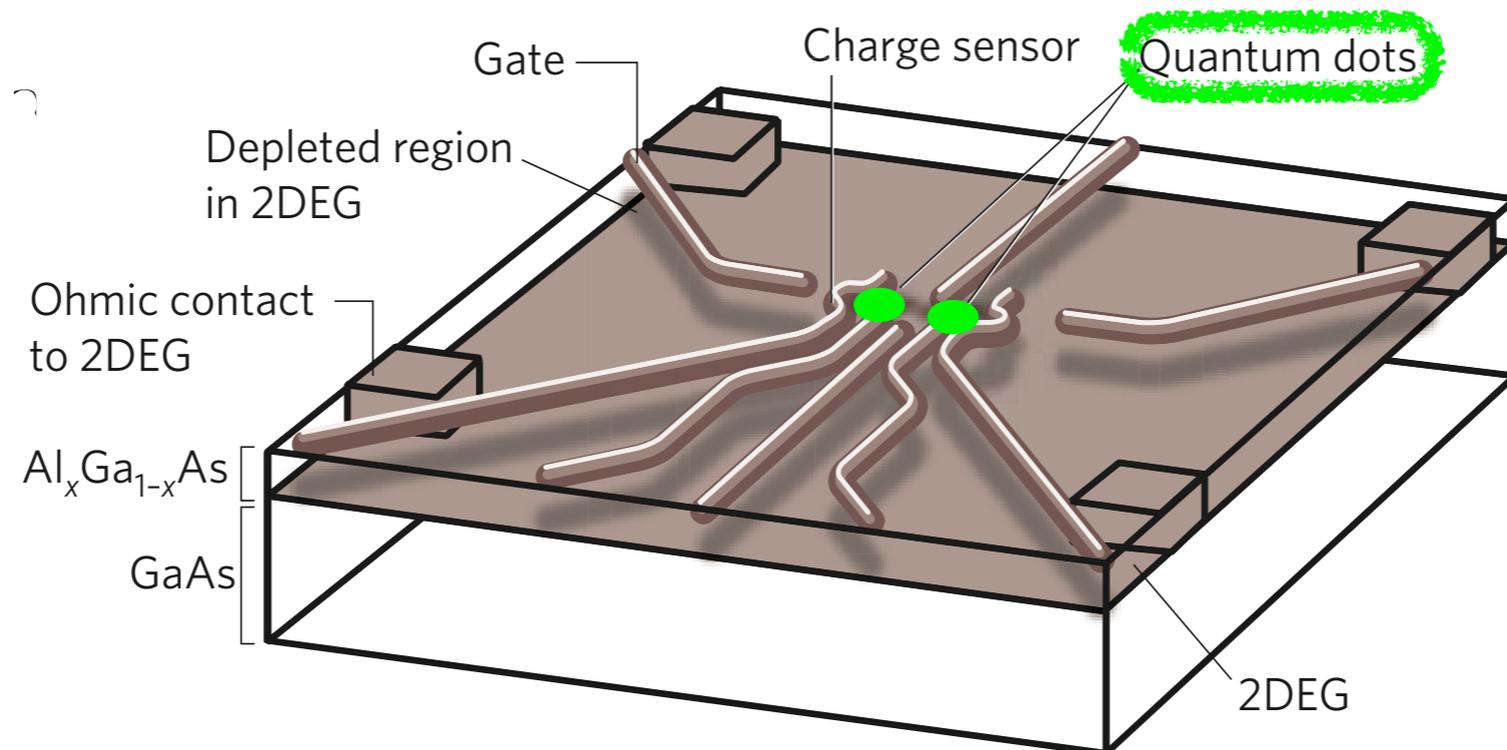
ábra: Hanson & Awschalom, Nature 2008

# Bevezetés - kettős kvantumdotok



ábra: Hanson & Awschalom, Nature 2008

# Bevezetés - spinblokád

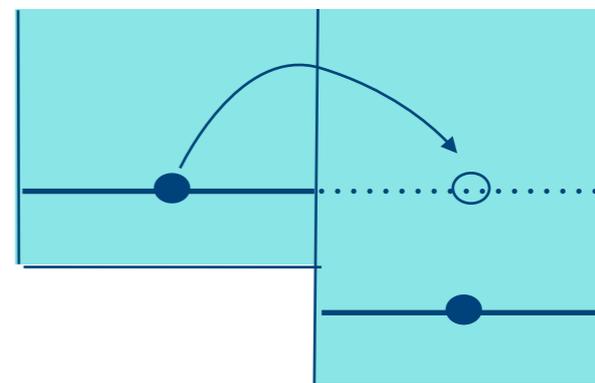


$$|s, m_s\rangle$$

1 szinglet

$$|0, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$S$



3 triplet

$$|1, 1\rangle = |\uparrow\uparrow\rangle$$

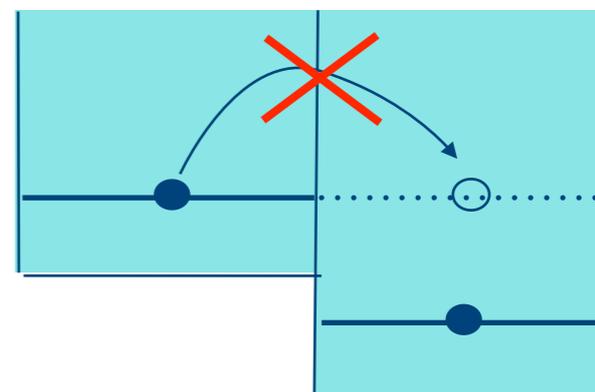
$$|1, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1, -1\rangle = |\downarrow\downarrow\rangle$$

$T_+$

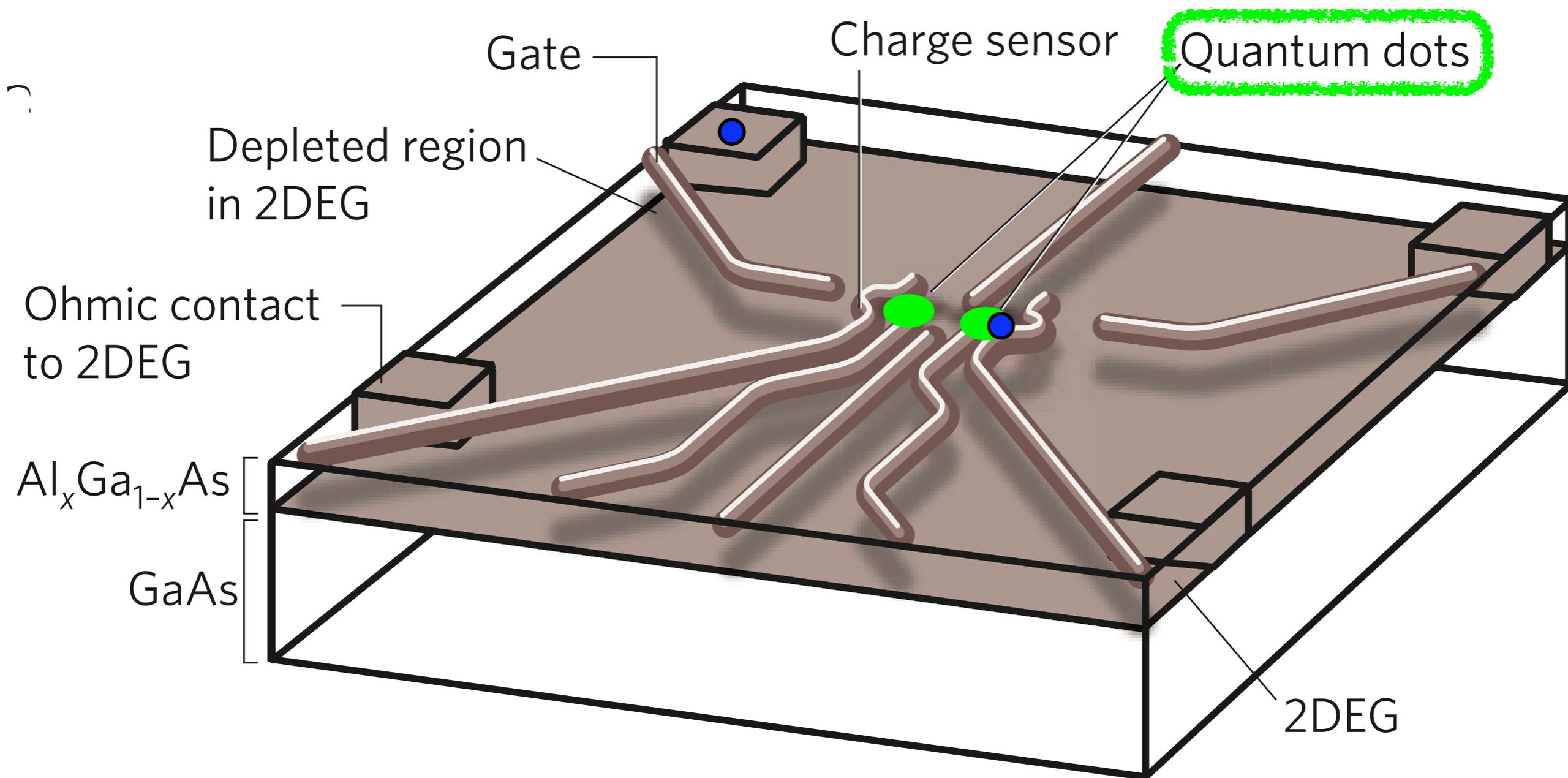
$T_0$

$T_-$



# Bevezetés - spinblokád

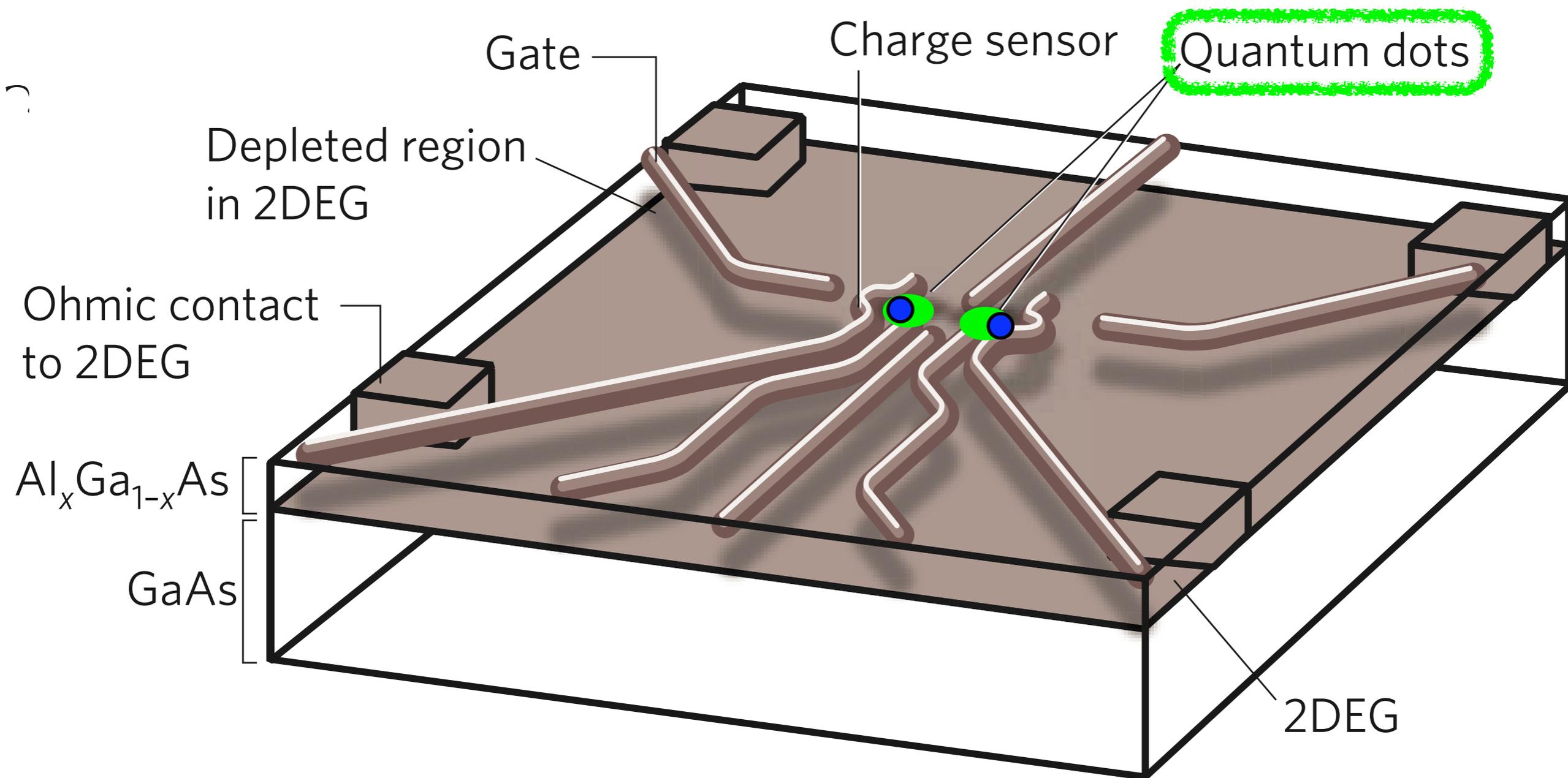
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(0,1)

# Bevezetés - spinblokáád

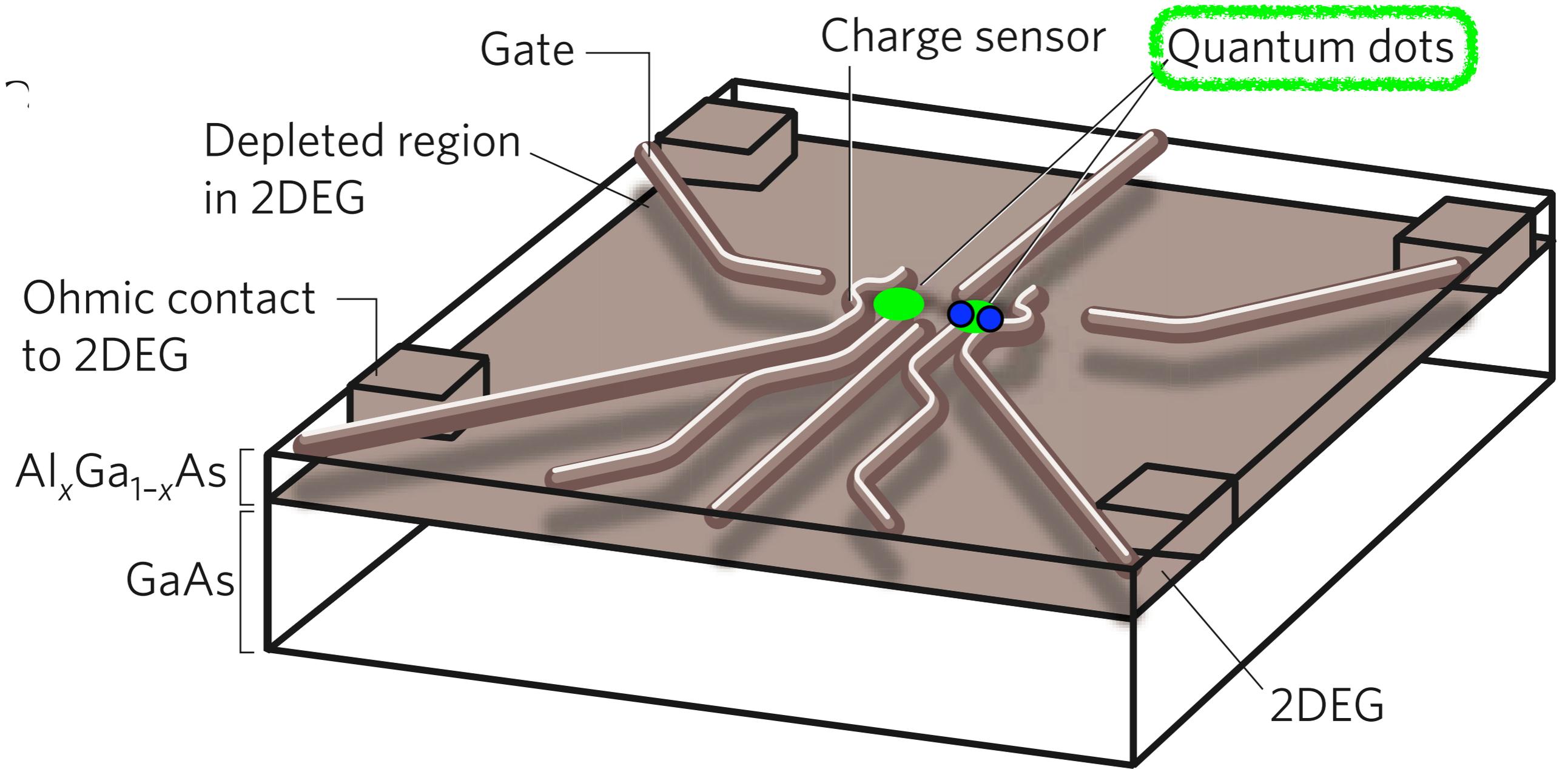
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(1,1)

# Bevezetés - spinblokád

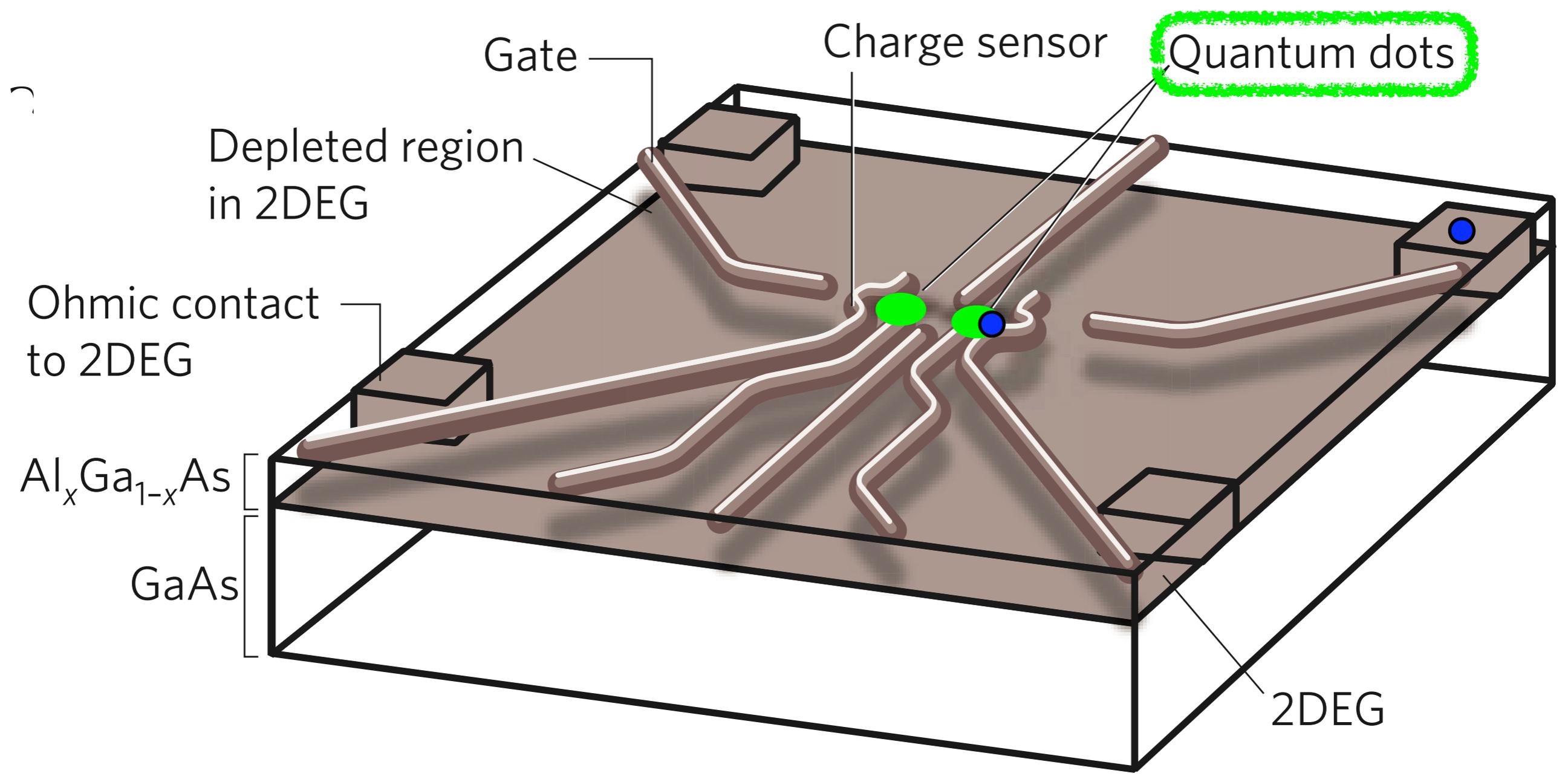
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(0,2)

# Bevezetés - spinblokád

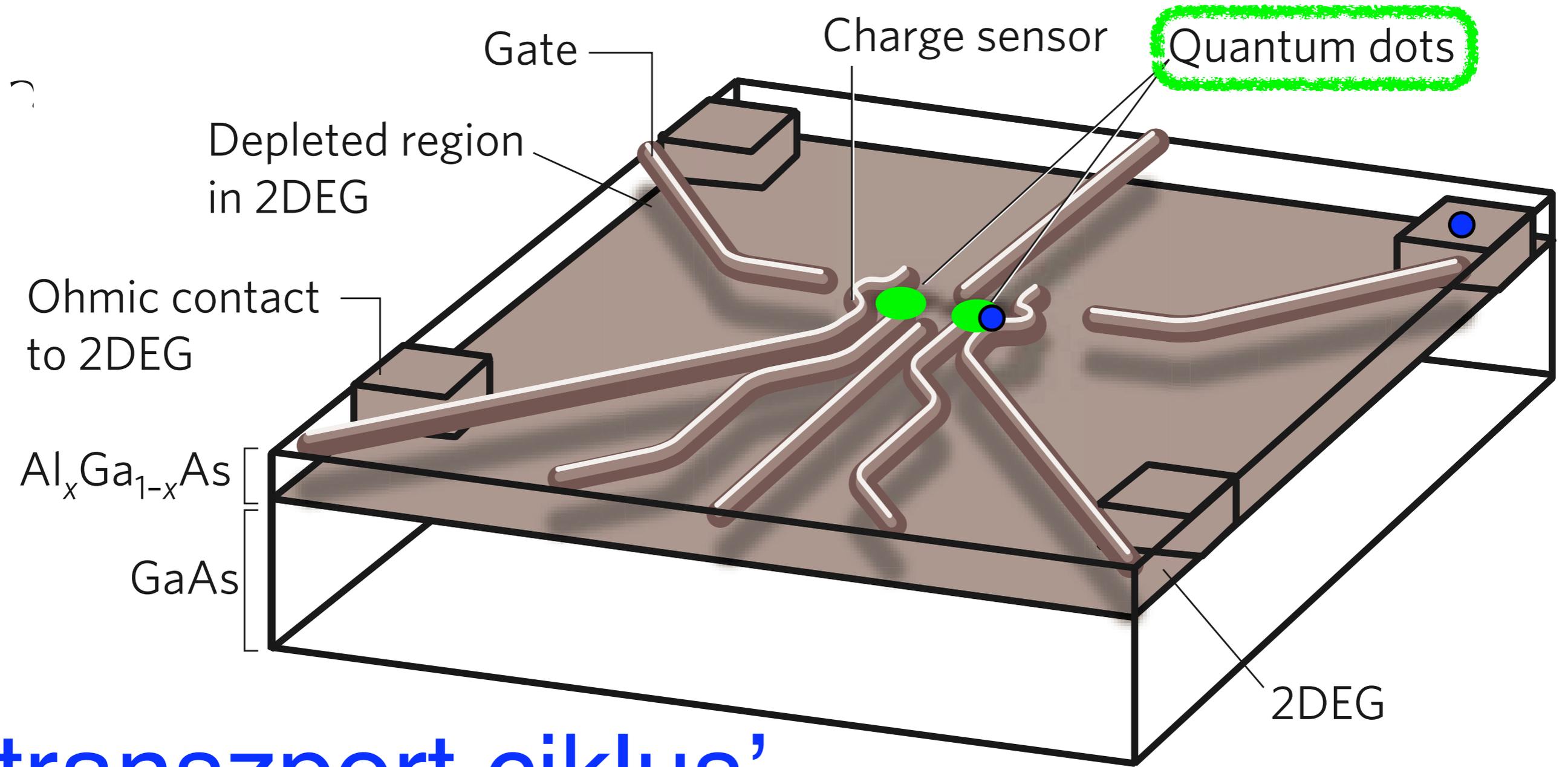
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(0,1)

# Bevezetés - spinblokád

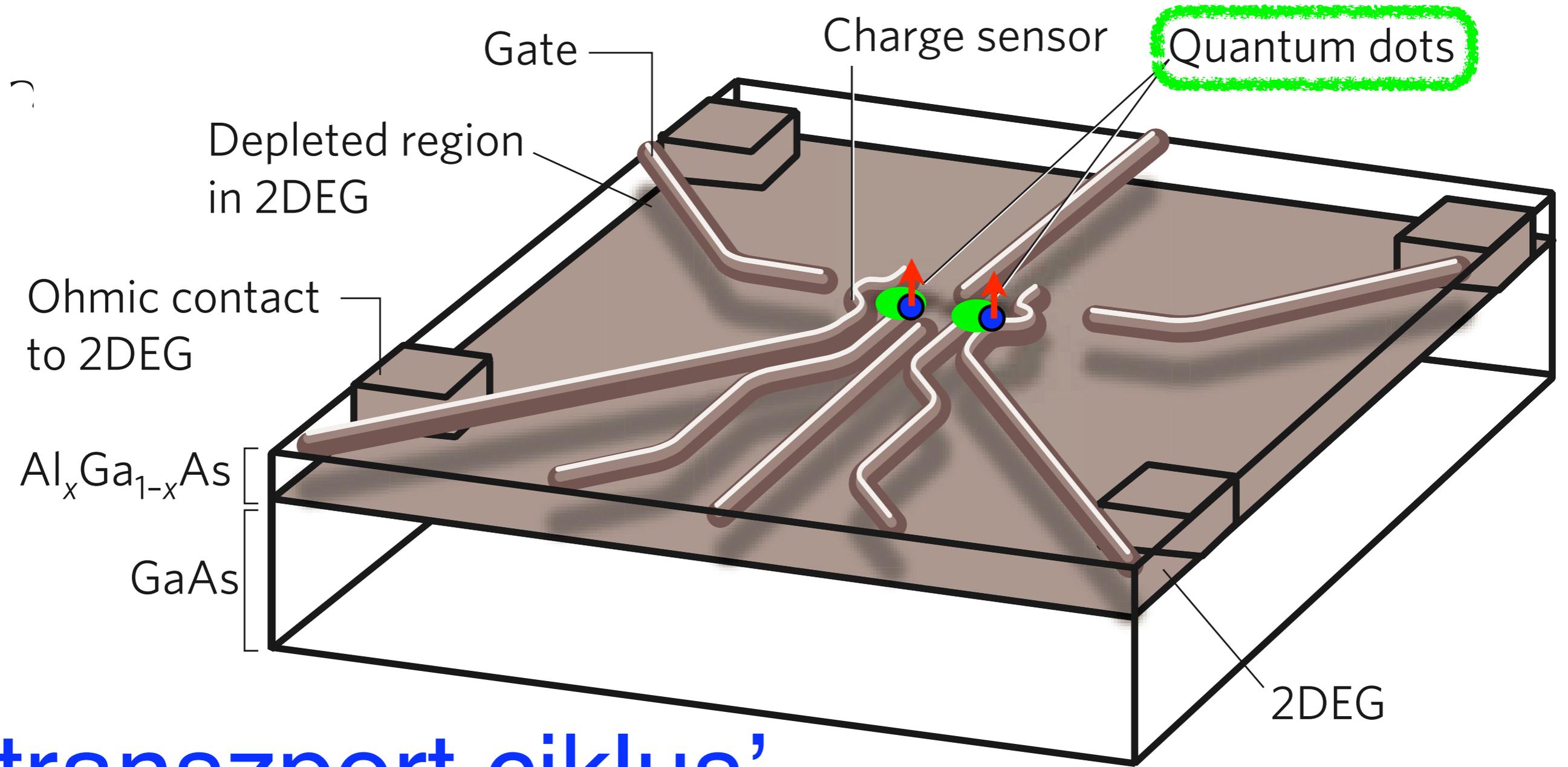
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



‘transzport ciklus’  
 $(0, 1) \text{--} (1, 1) \text{--} (0, 2) \text{--} (0, 1)$

# Bevezetés - spinblokád

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‘transzport ciklus’

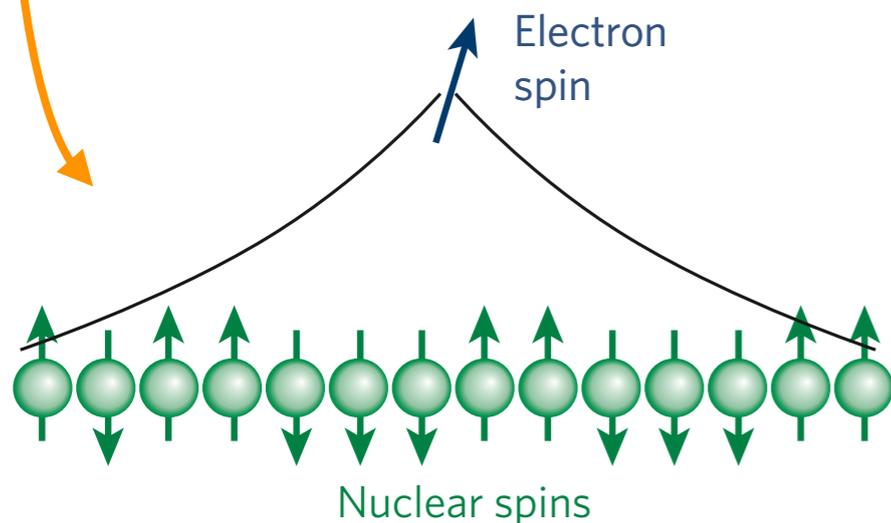
$$(0, 1) \text{ -- } (1, 1) \times (0, 2) \text{ -- } (0, 1)$$

stacionárius állapot:  
áram = 0

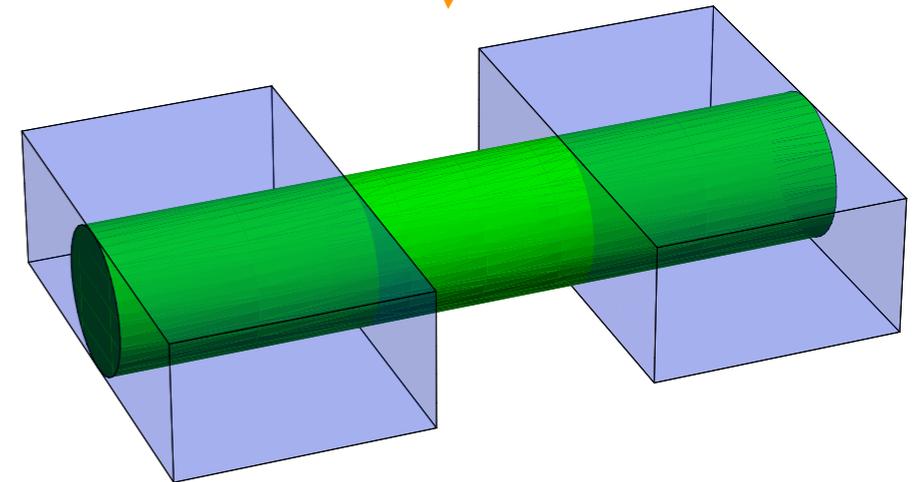
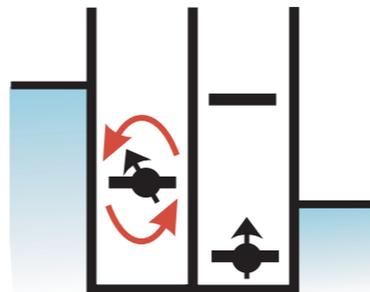
# Tartalom

(Spinblokádkettős kvantumdotokban)

- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok



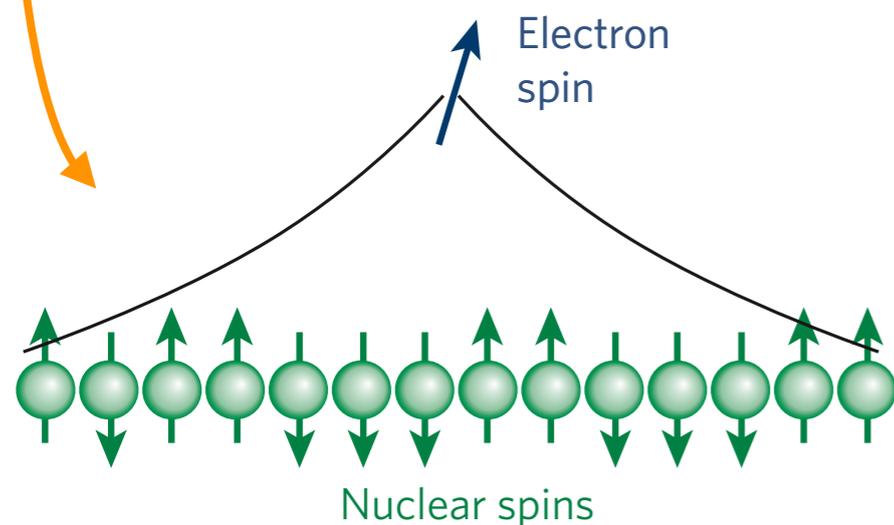
Spin  
manipulation



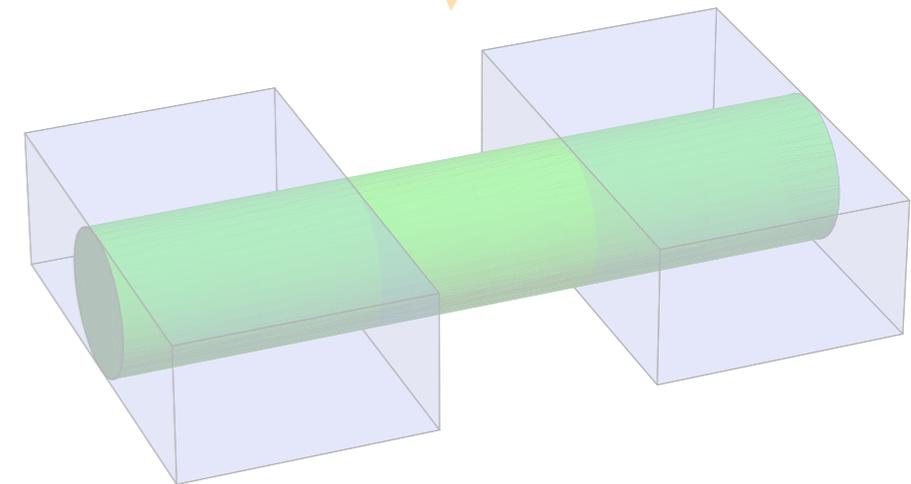
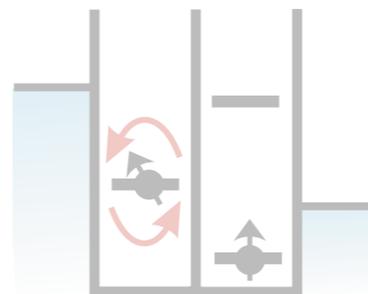
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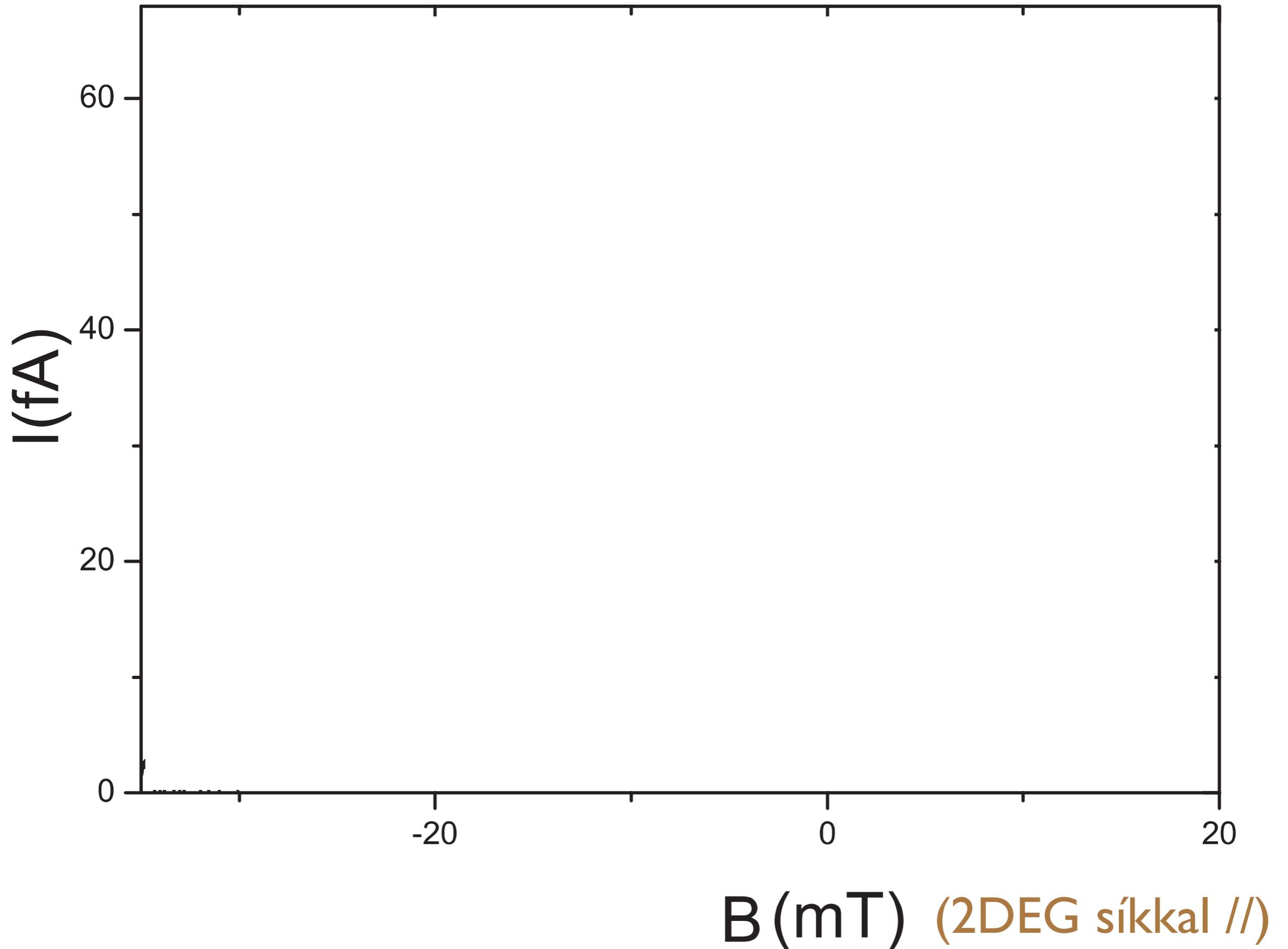


Spin  
manipulation



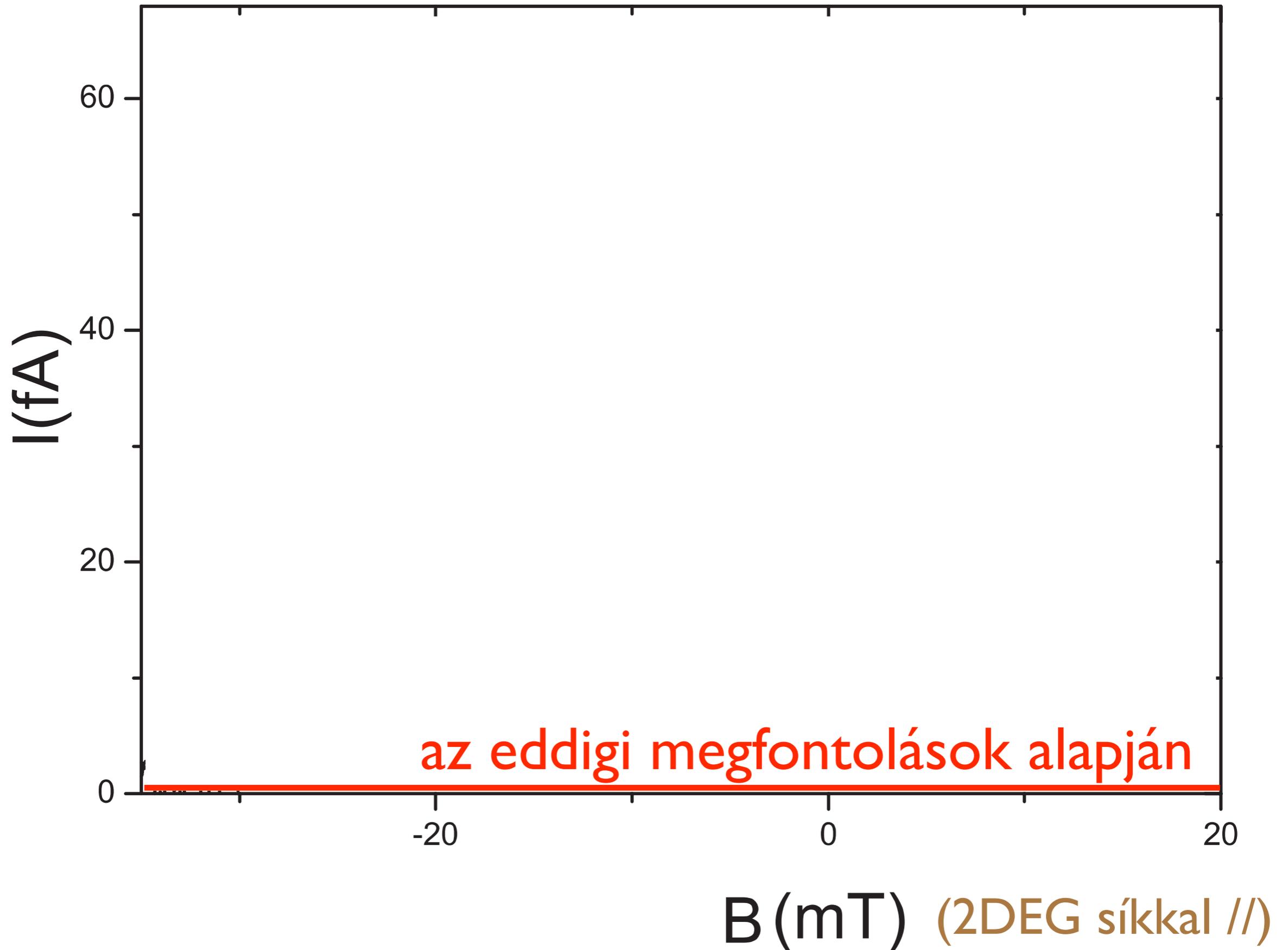
# Spinblokáád - mérés

Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



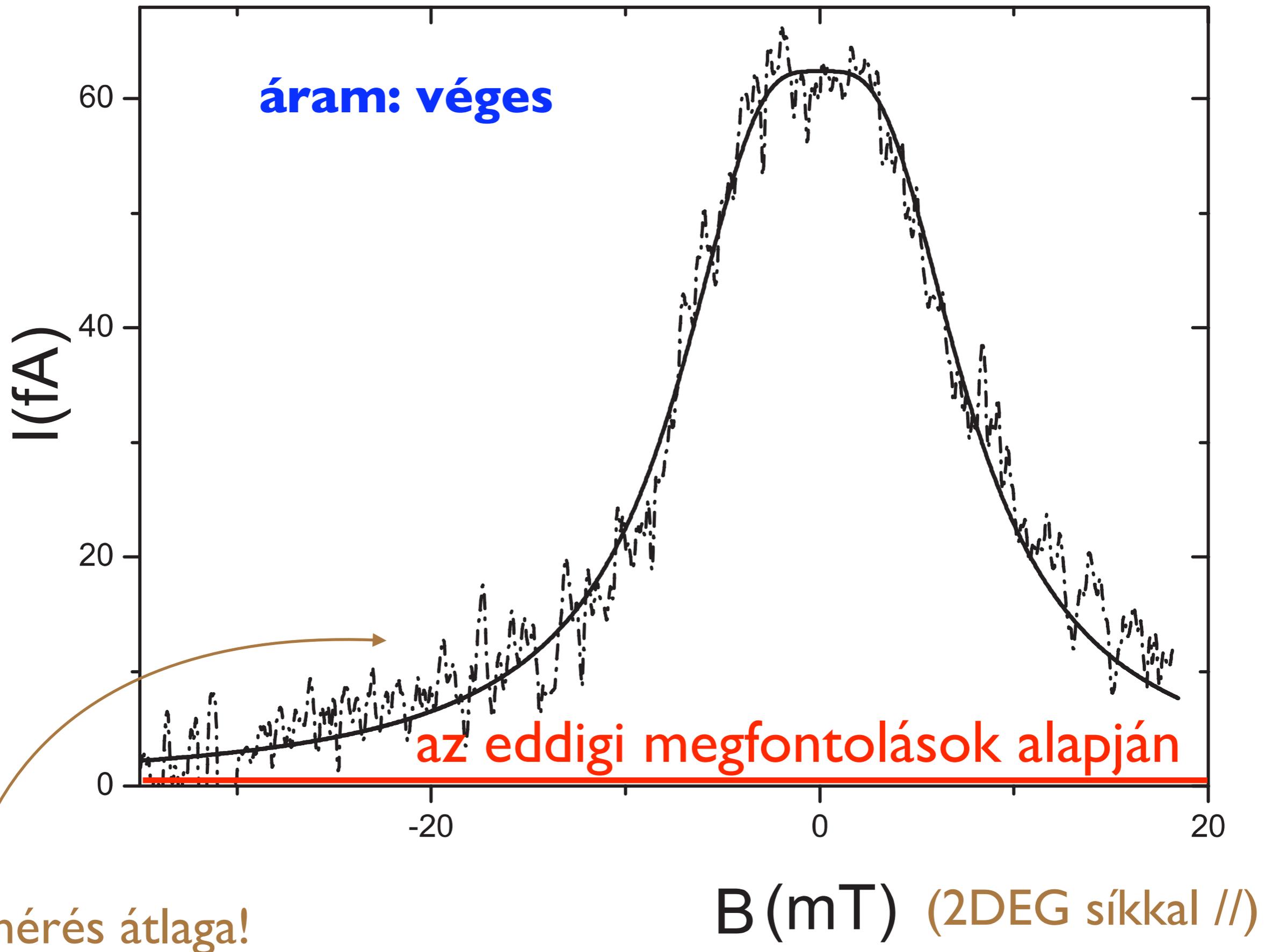
# Spinblokáád - mérés

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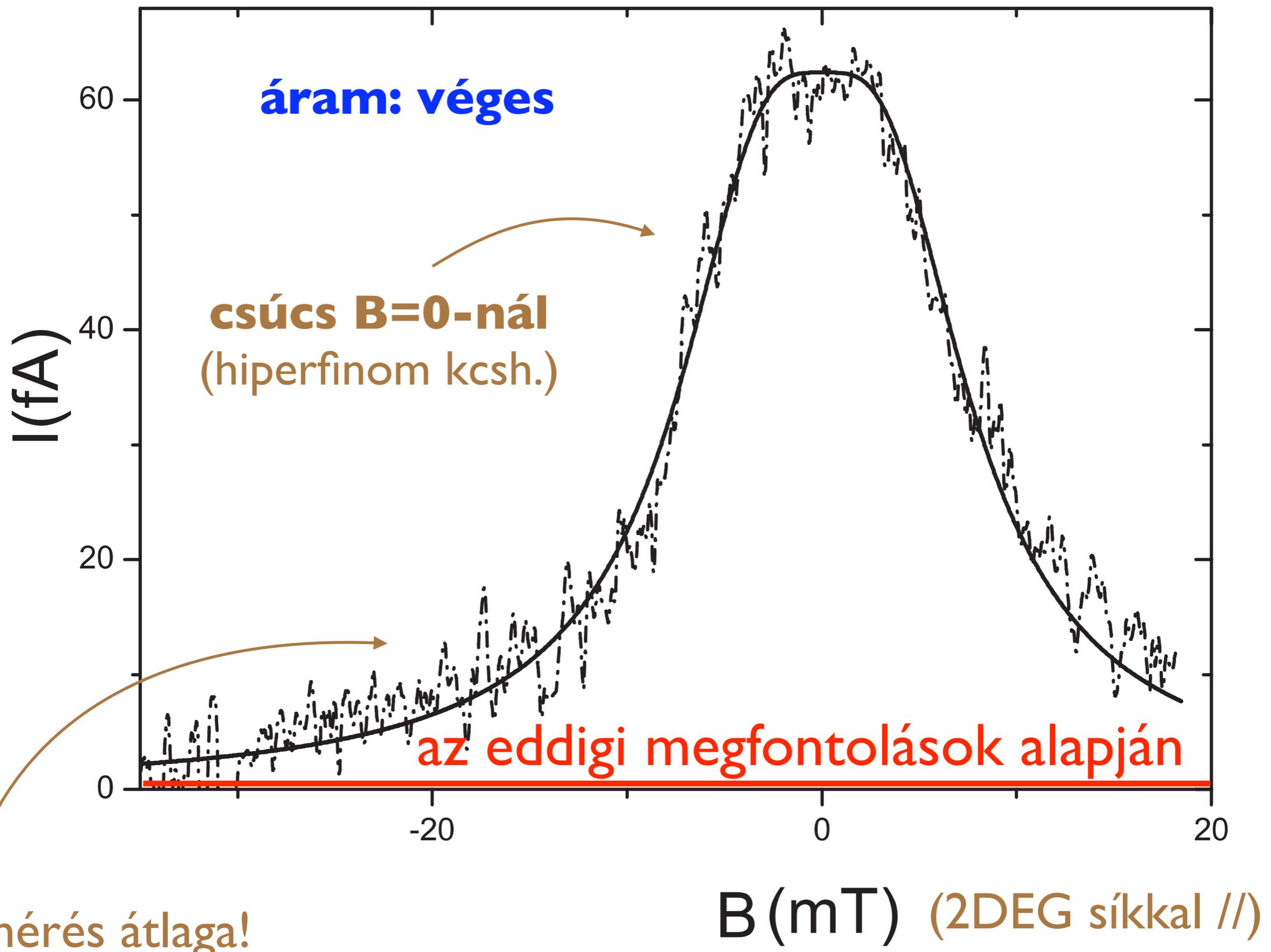
# Spinblokáád - mérés

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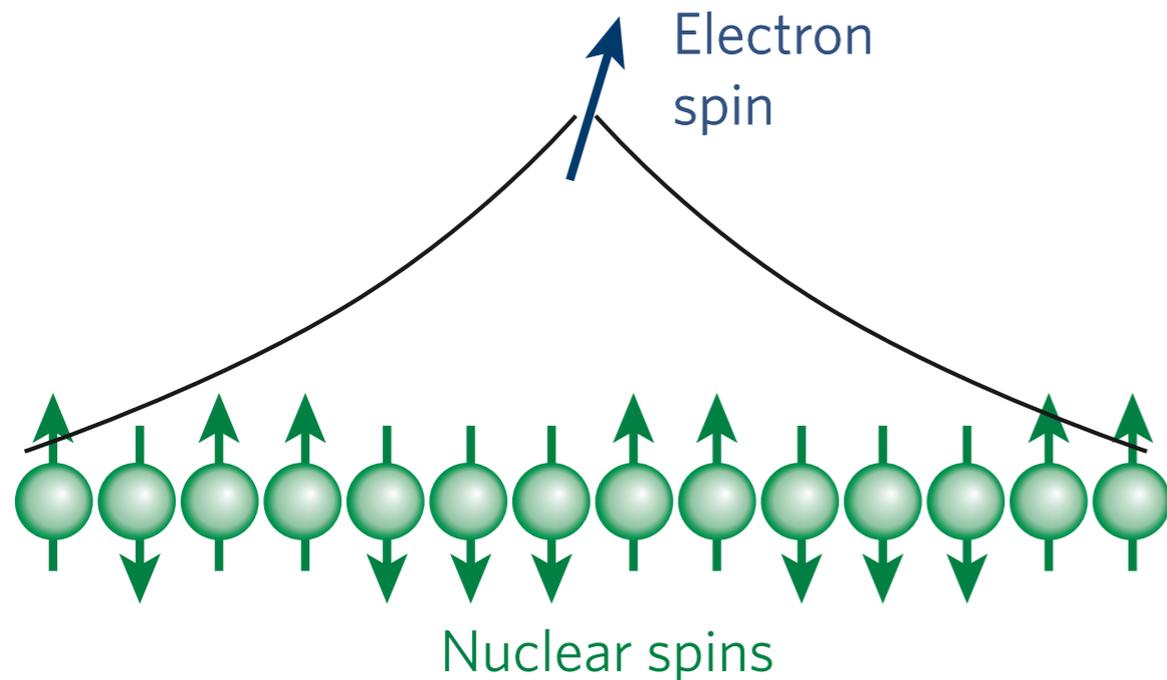


# Spinblokáád - mérés

Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



# Hiperfinom kölcsönhatás kvantumdotokban



ábra: Hanson & Awschalom, Nature 2008

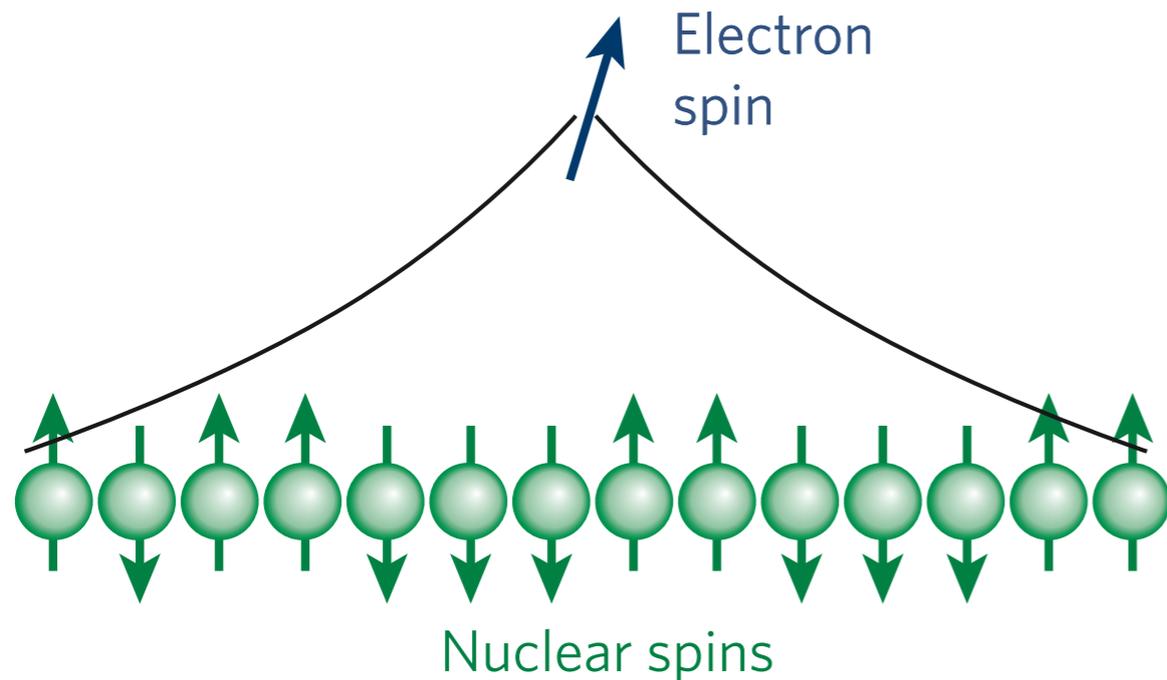
$$h_1^k = \frac{\mu_0}{4\pi} \frac{8\pi}{3} \gamma_S \gamma_{j_k} \delta(\mathbf{r}_k) \mathbf{S} \cdot \mathbf{I}_k, \quad (\text{pl. GaAs, vezetési sáv: s-pályák})$$

**izotrop** hf-kcsh

$$h_2^k = \frac{\mu_0}{4\pi} \gamma_S \gamma_{j_k} \frac{3(\mathbf{n}_k \cdot \mathbf{S})(\mathbf{n}_k \cdot \mathbf{I}_k) - \mathbf{S} \cdot \mathbf{I}_k}{r_k^3 (1 + d/r_k)},$$

**dipólus** hf-kcsh  
(pl. szén, p-pályák)

# Hiperfinom kölcsönhatás kvantumdotokban



ábra: Hanson & Awschalom, Nature 2008

GaAs kvantumdot:

$$H_{\text{hf, GaAs}} = \mathbf{S} \cdot \mathbf{h}$$

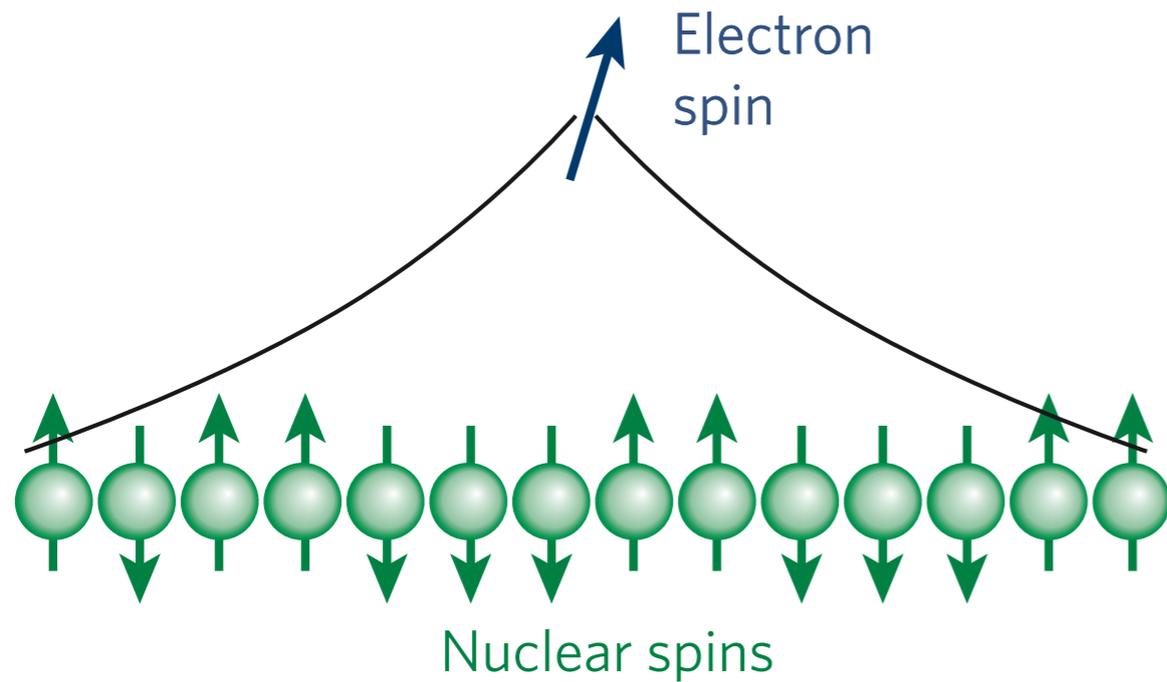
$$h_1^k = \frac{\mu_0}{4\pi} \frac{8\pi}{3} \gamma_S \gamma_{j_k} \delta(\mathbf{r}_k) \mathbf{S} \cdot \mathbf{I}_k, \text{ (pl. GaAs, vezetési sáv: s-pályák)}$$

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ábra: Hanson & Awschalom, Nature 2008

GaAs kvantumdot:

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effektív mágneses tér

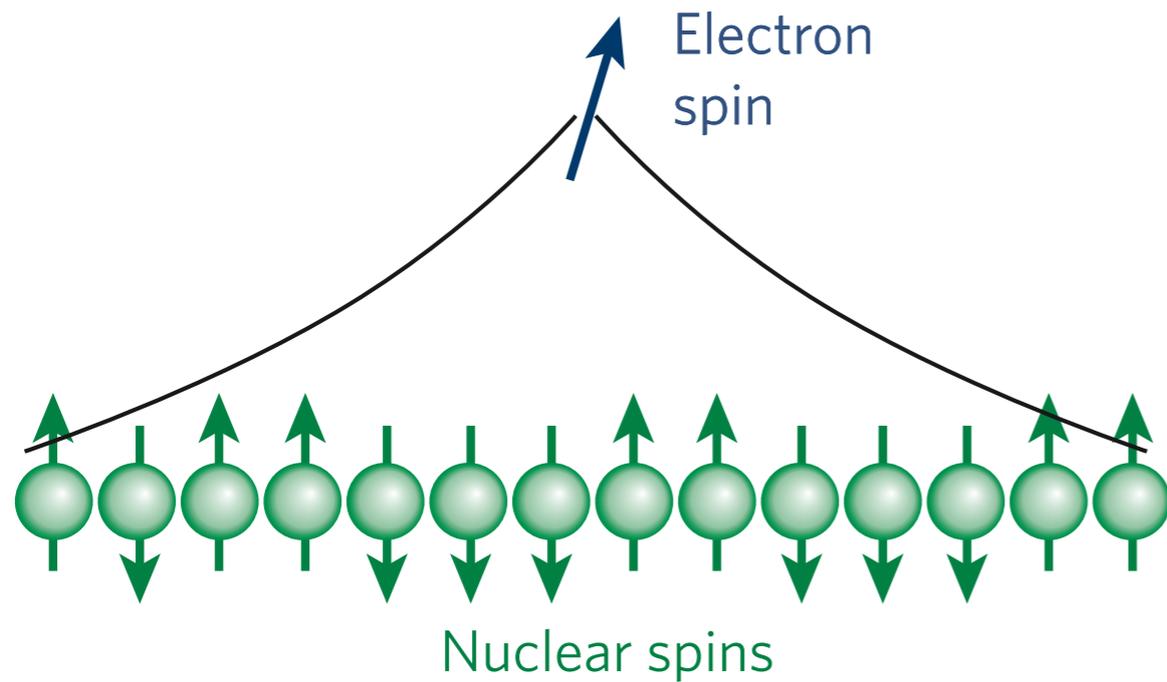
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ábra: Hanson & Awschalom, Nature 2008

GaAs kvantumdot:

$$H_{\text{hf, GaAs}} = \mathbf{S} \cdot \mathbf{h}$$

effektív mágneses tér  
**véletlen** irány és nagyság  
 $\text{StdDev}(h_{x,y,z}) \propto A/\sqrt{N}$

$$h_1^k = \frac{\mu_0}{4\pi} \frac{8\pi}{3} \gamma_S \gamma_{j_k} \delta(\mathbf{r}_k) \mathbf{S} \cdot \mathbf{I}_k, \text{ (pl. GaAs, vezetési sáv: s-pályák)}$$

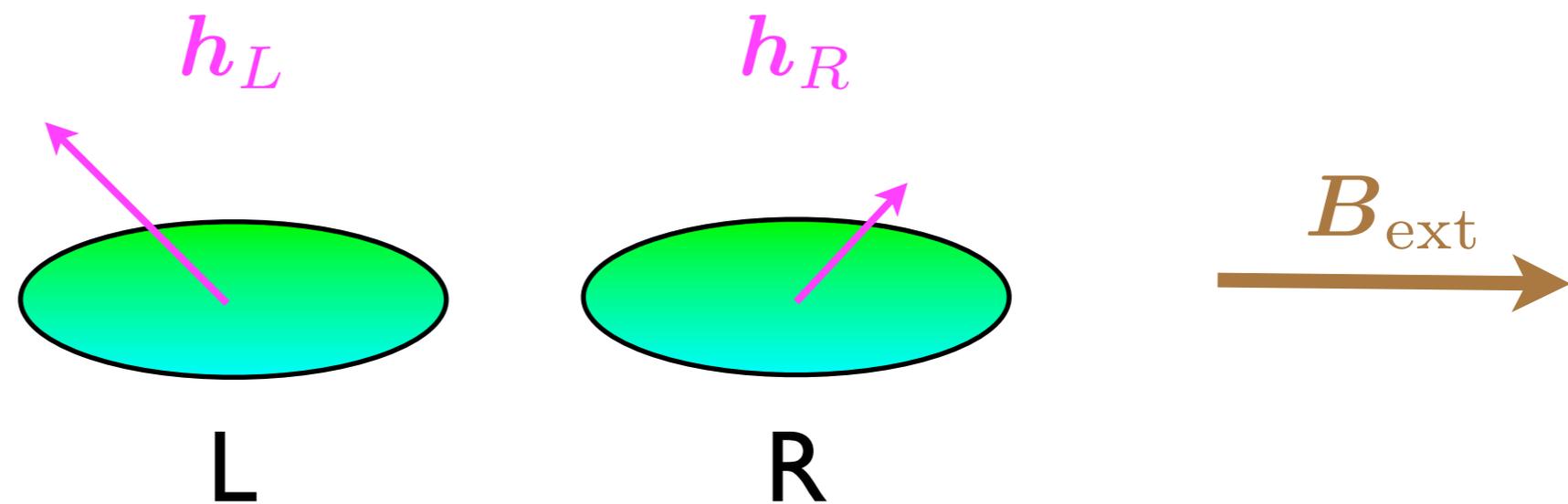
**izotrop** hf-kcsh

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**dipólus** hf-kcsh  
 (pl. szén, p-pályák)

# Hiperfinom kölcsönhatás a szinglet-triplet bázisban

$$H_{\text{spin}} = \underbrace{\mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R}_{\text{hiperfinom kölcsönhatás}} + \underbrace{(\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}}_{\text{Zeeman-effektus}}$$

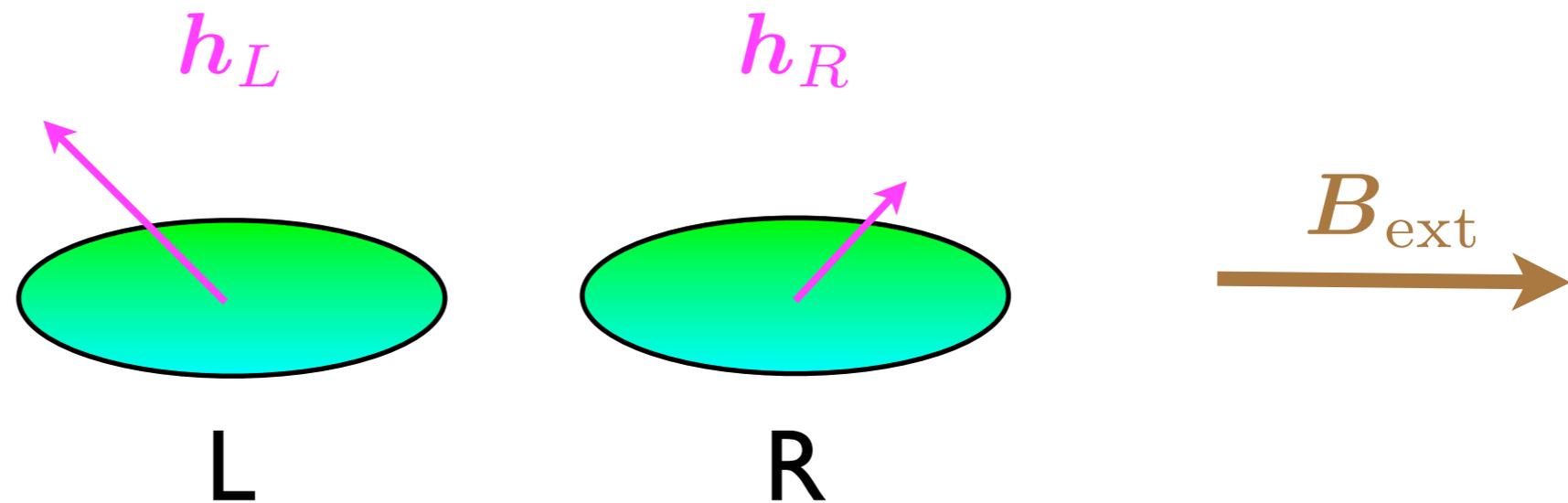


# Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás      Zeeman-effektus

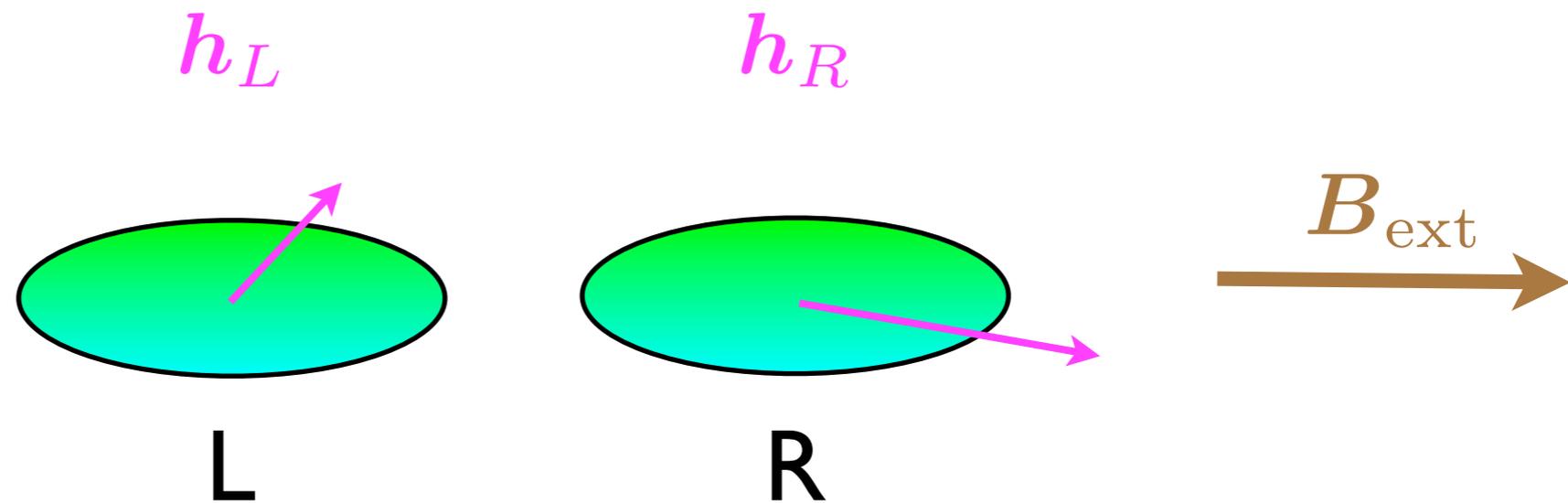


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hiperfinom kölcsönhatás      Zeeman-effektus

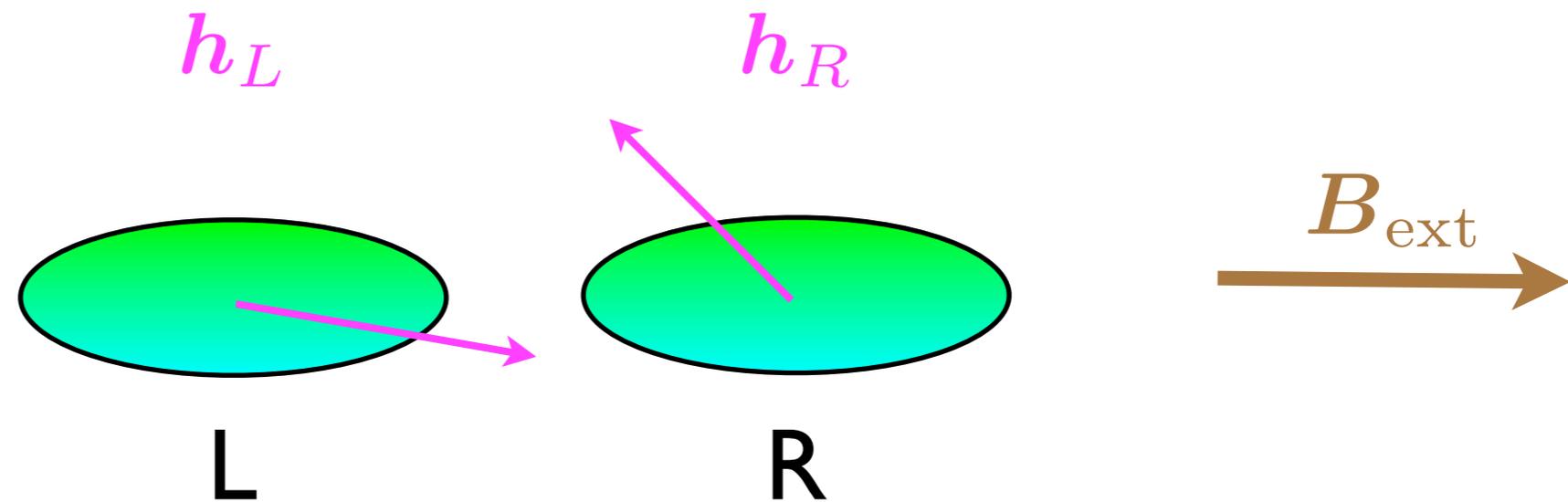


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hiperfinom kölcsönhatás      Zeeman-effektus

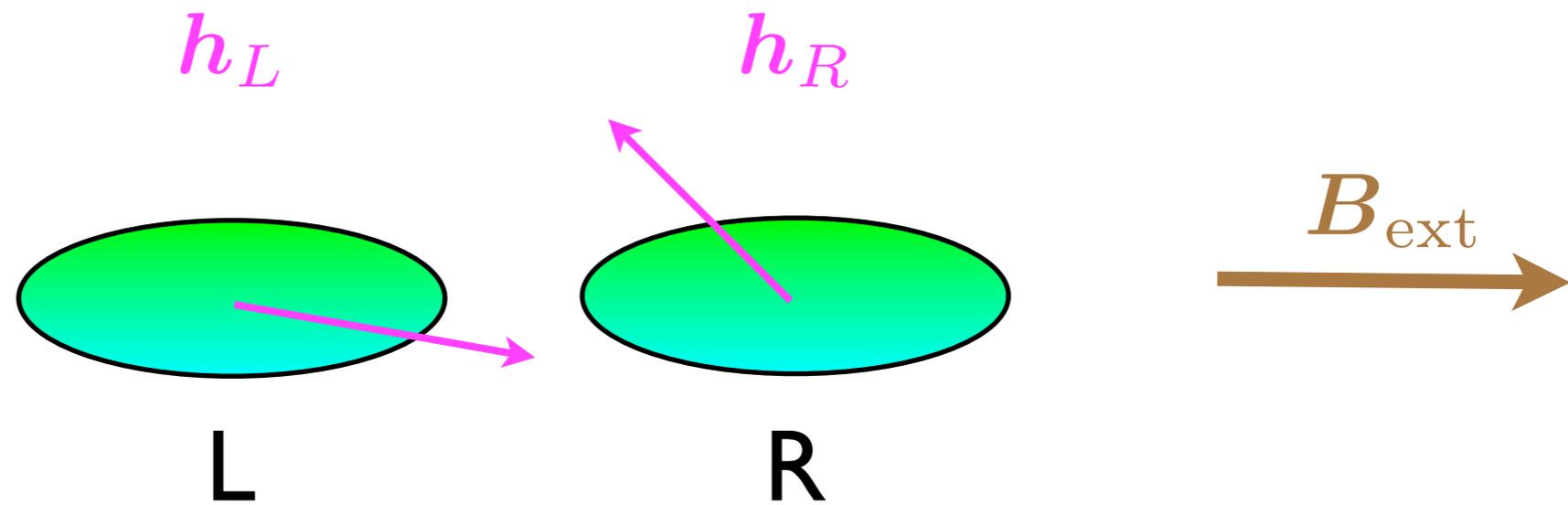


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hiperfinom kölcsönhatás      Zeeman-effektus



„szimmetrikus  
komponens”

$$\mathbf{B}_s \equiv \frac{\mathbf{h}_L + \mathbf{h}_R}{2} + \mathbf{B}_{\text{ext}}$$

„antiszimmetrikus  
komponens”

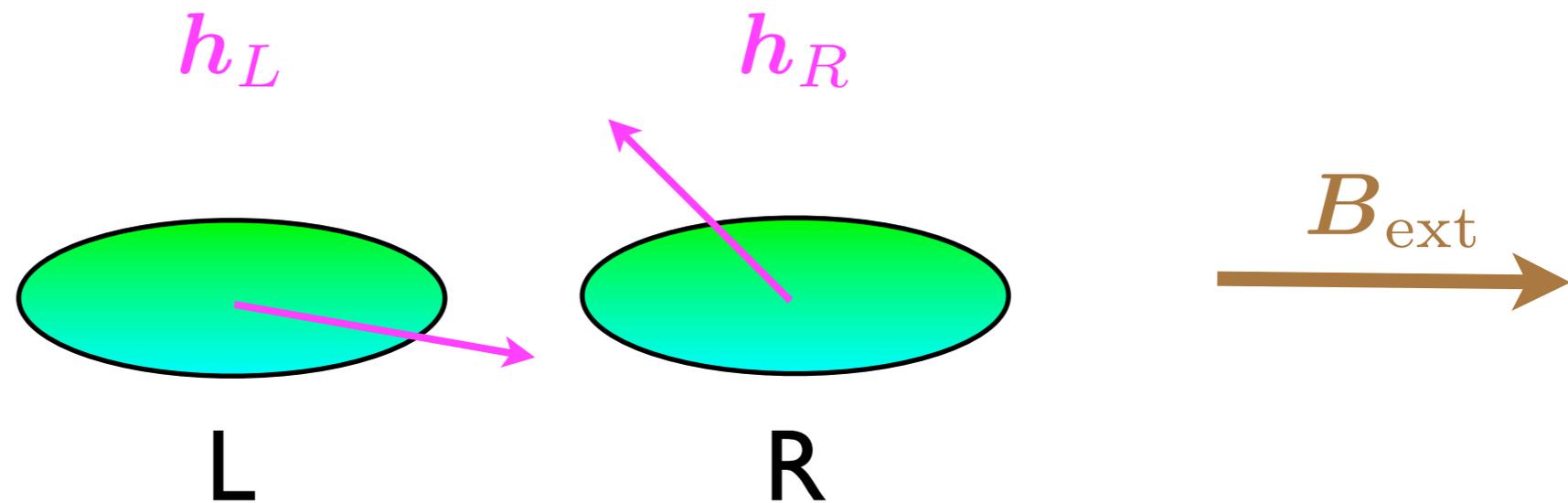
$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

# Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás      Zeeman-effektus



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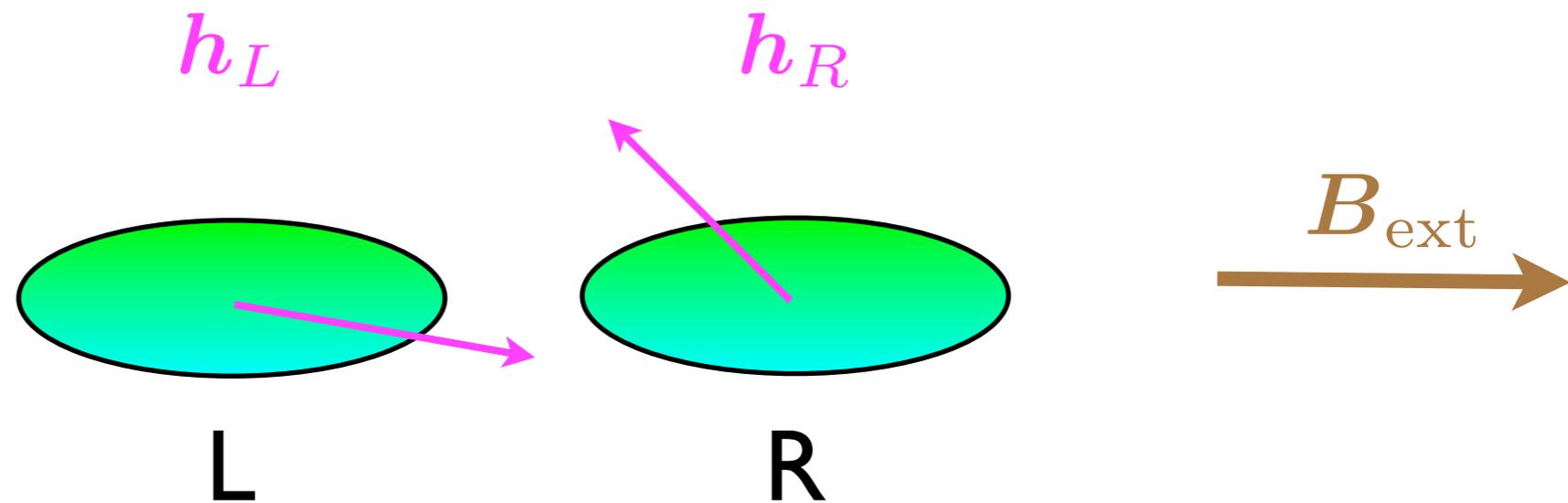
$$\hat{H}_{\text{spin}} = B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| + B_a^z |S\rangle\langle T_0| + \sum_{\pm} \left( \frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

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hiperfinom kölcsönhatás      Zeeman-effektus



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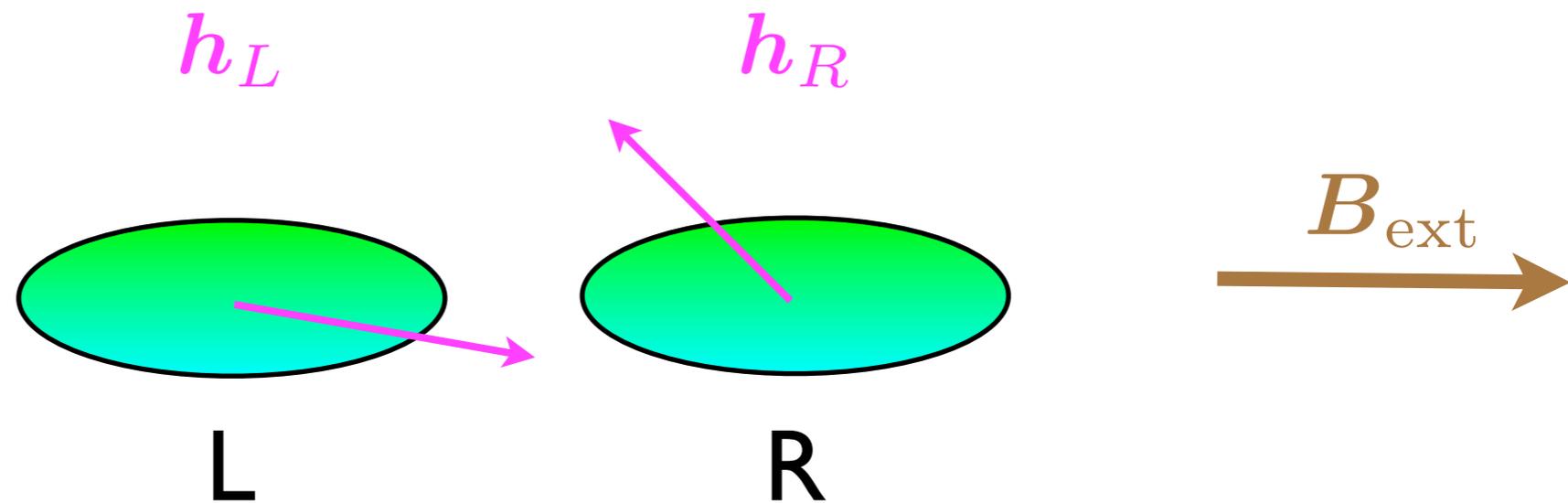
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hiperfinom kölcsönhatás      Zeeman-effektus



„szimmetrikus komponens”

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„antiszimmetrikus komponens”

$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

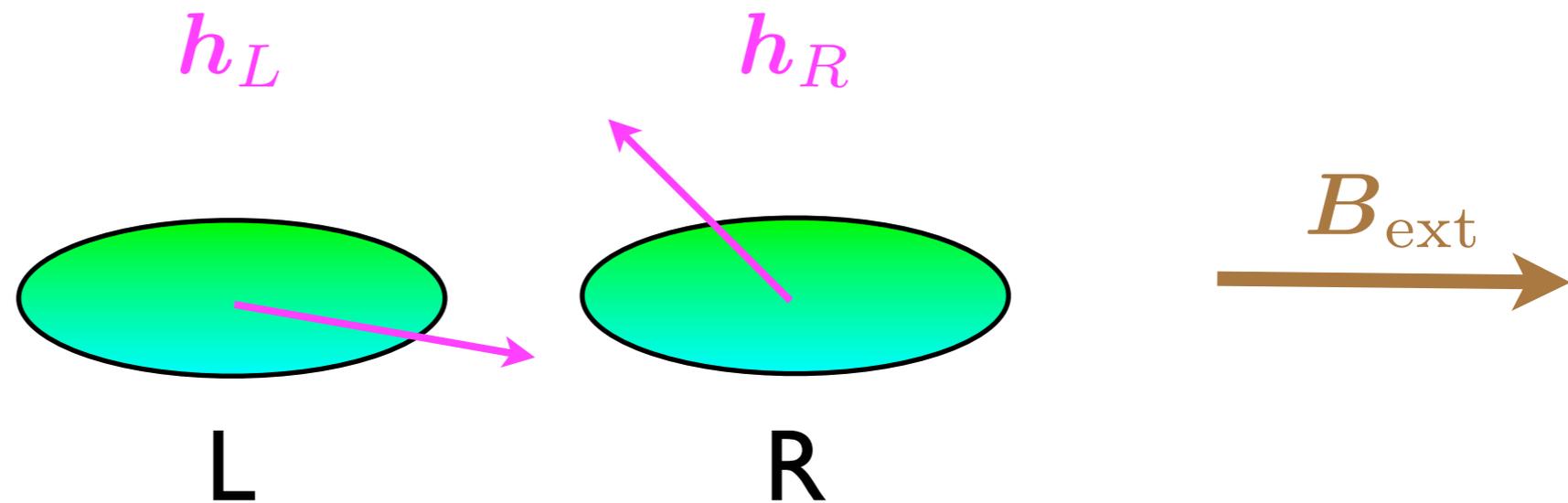
$$\hat{H}_{\text{spin}} = \left( B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| \right) + \left( B_a^z |S\rangle\langle T_0| \right) + \sum_{\pm} \left( \frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

# Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás      Zeeman-effektus



„szimmetrikus komponens”

$$\mathbf{B}_s \equiv \frac{\mathbf{h}_L + \mathbf{h}_R}{2} + \mathbf{B}_{\text{ext}}$$

„antiszimmetrikus komponens”

$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

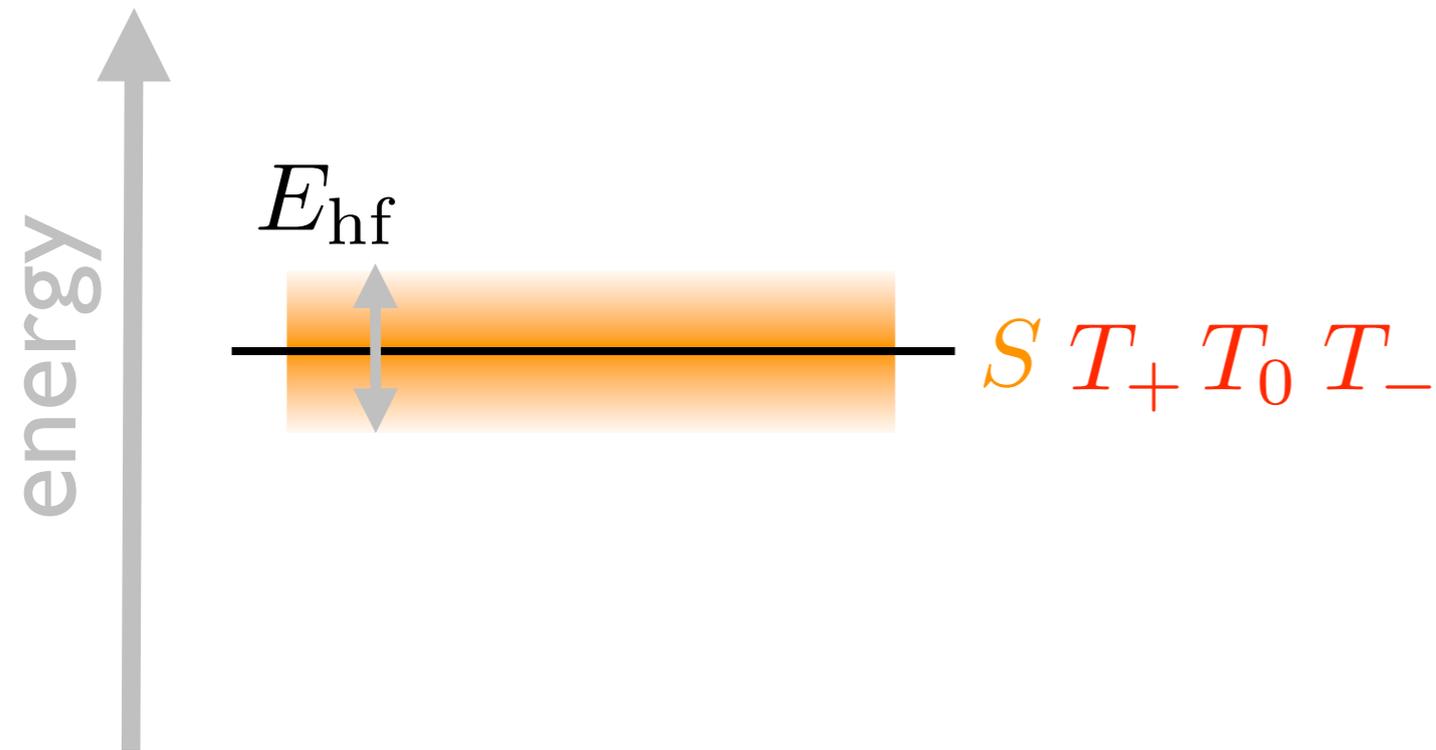
$$\hat{H}_{\text{spin}} = \left( B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| \right) + \left( B_a^z |S\rangle\langle T_0| \right) + \sum_{\pm} \left( \frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

**$B_a$ - szinglet-triplet csatolás**

# Áram mágneses térben

(1,1) energiaszintek

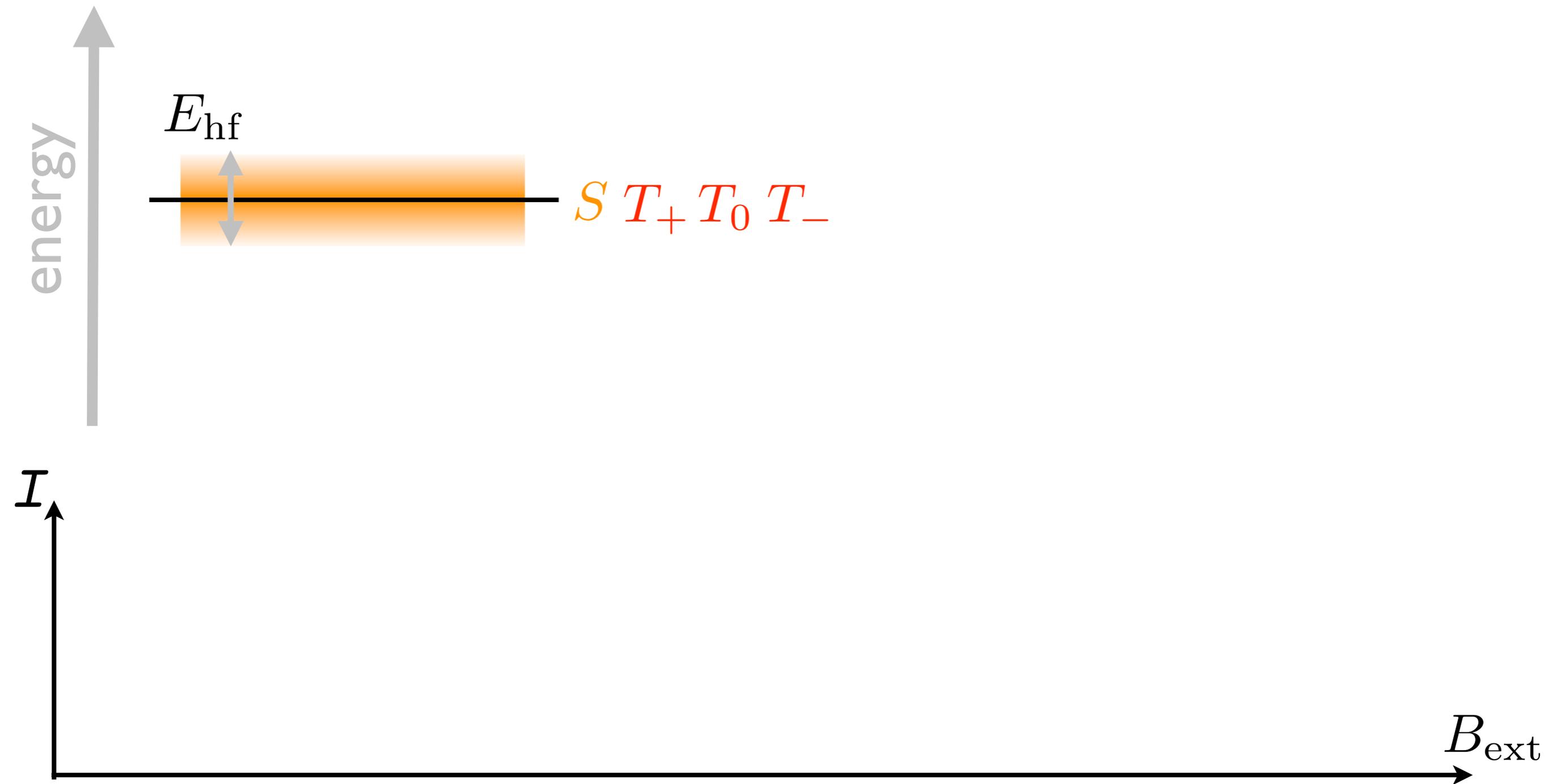
$$B_{\text{ext}} = 0$$



# Áram mágneses térben

(1,1) energiaszintek

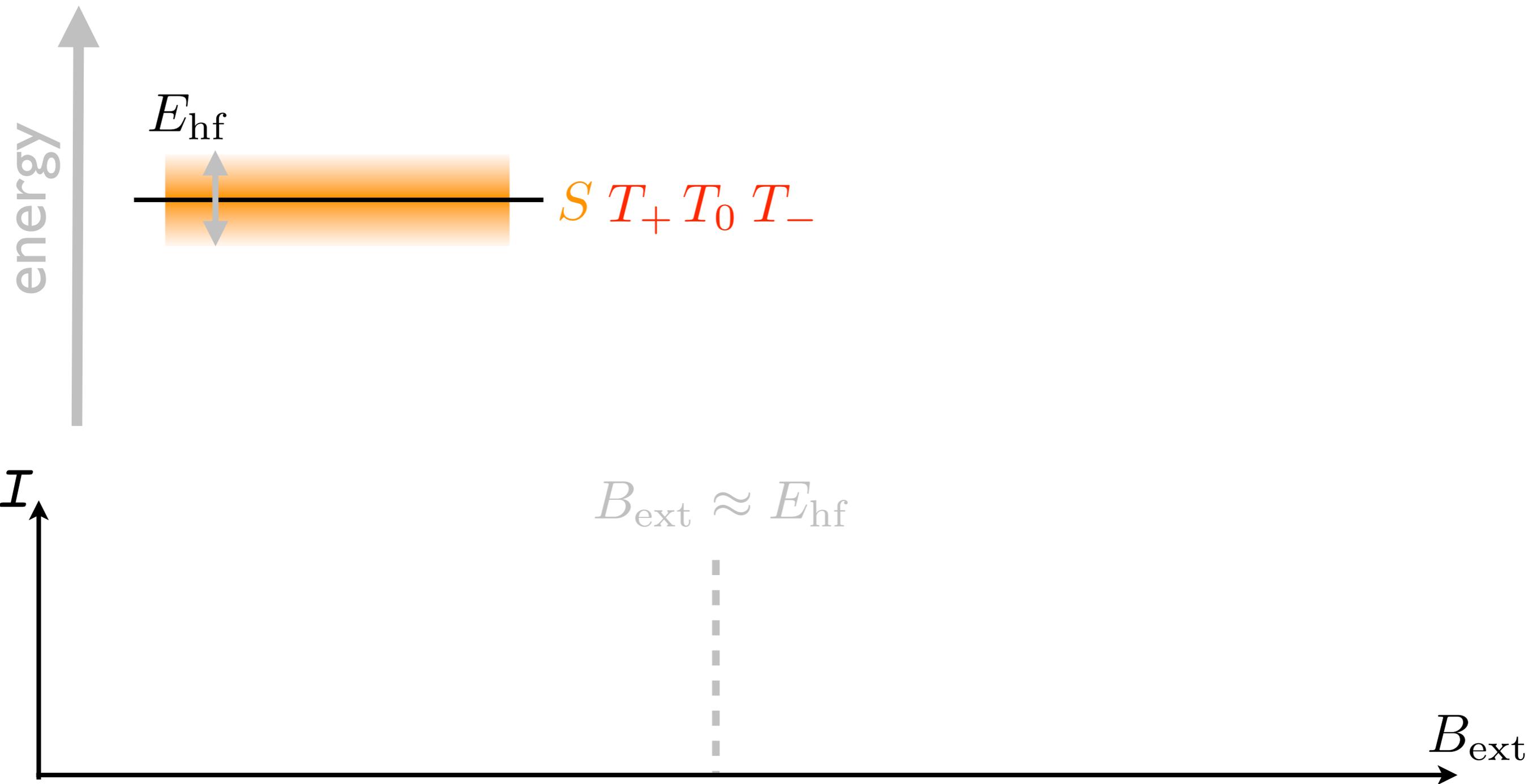
$$B_{\text{ext}} = 0$$



# Áram mágneses térben

(1,1) energiaszintek

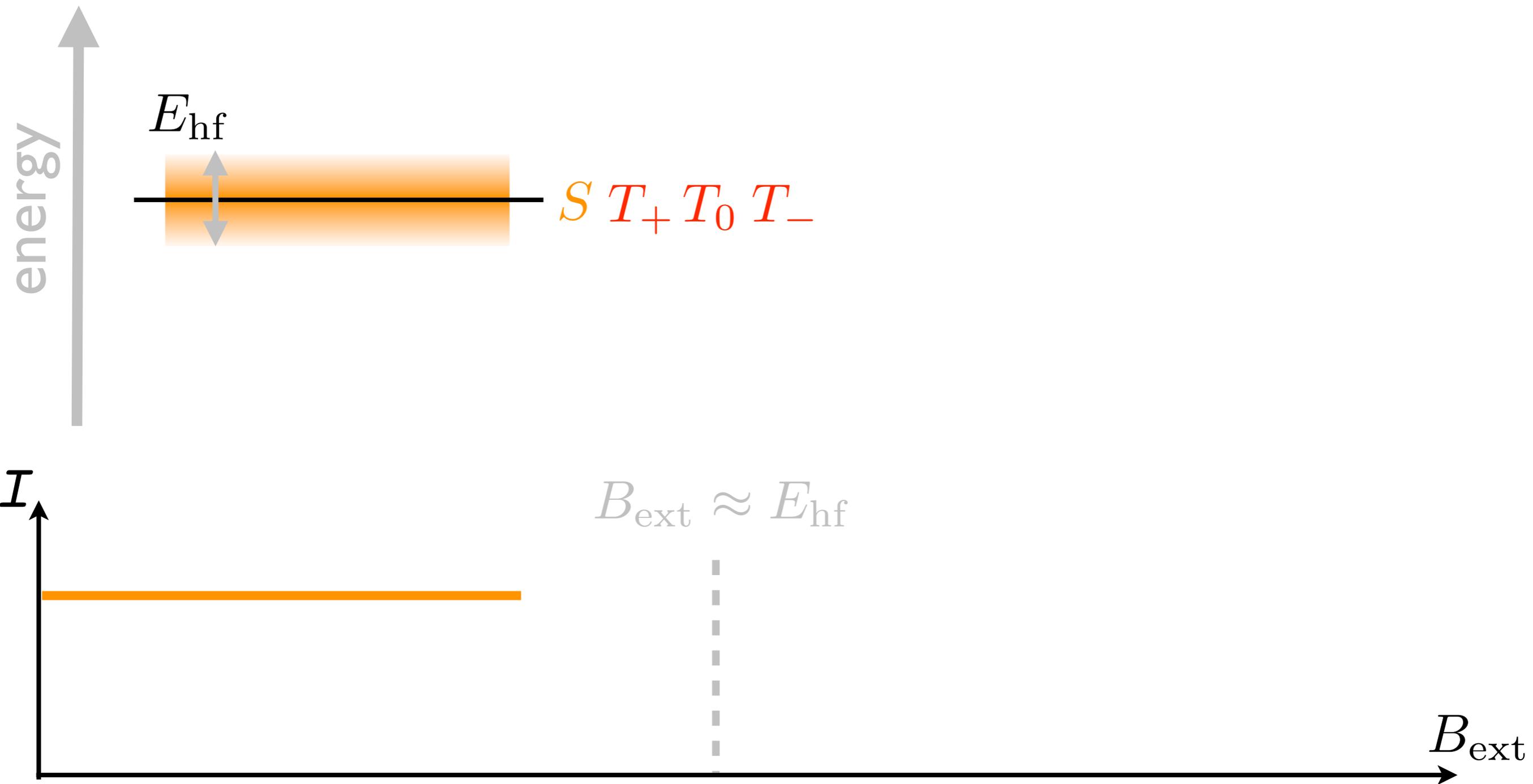
$$B_{\text{ext}} = 0$$



# Áram mágneses térben

(1,1) energiaszintek

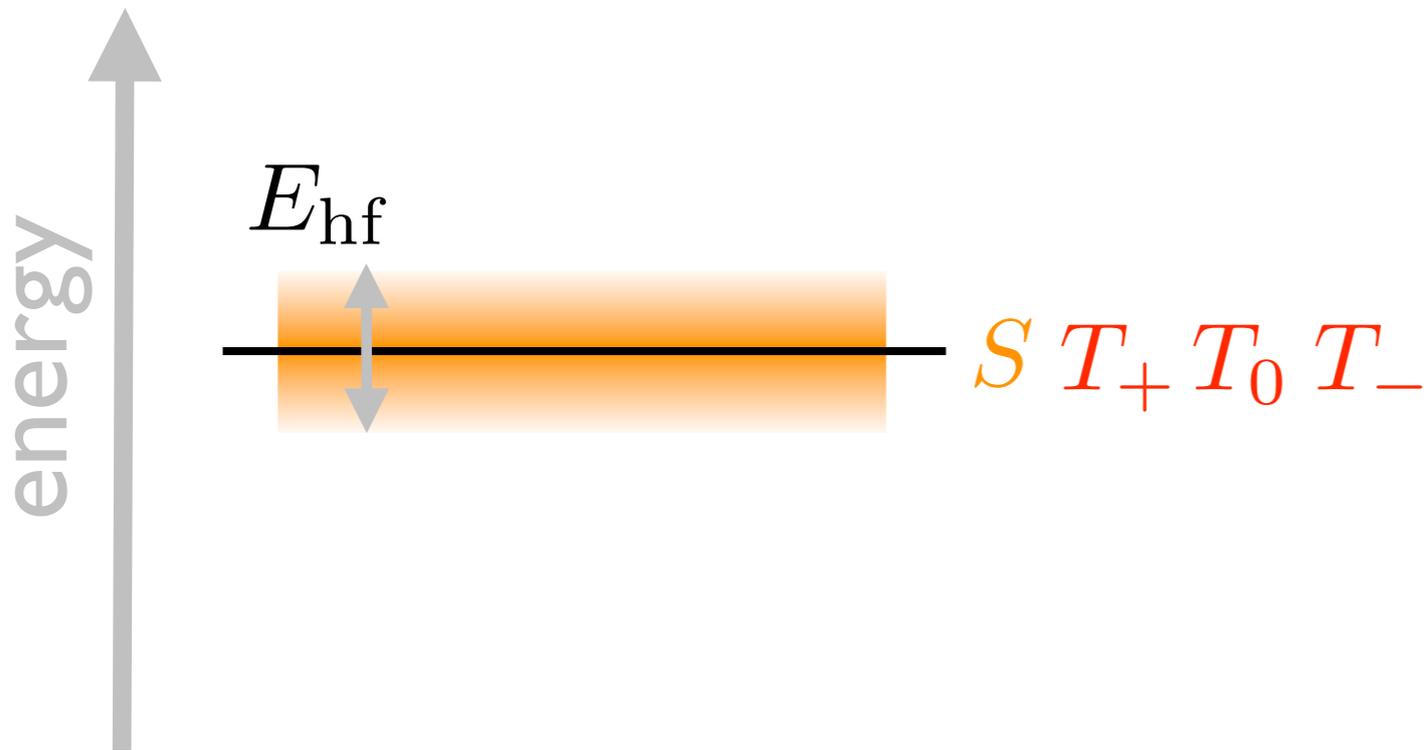
$$B_{\text{ext}} = 0$$



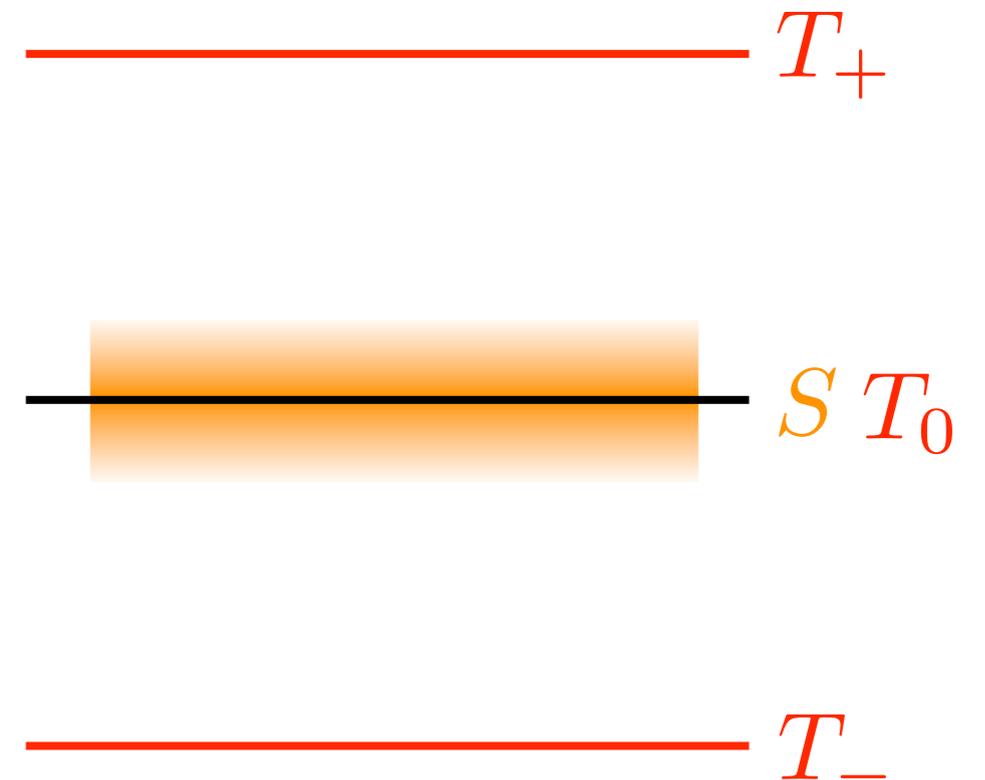
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## (1,1) energiaszintek

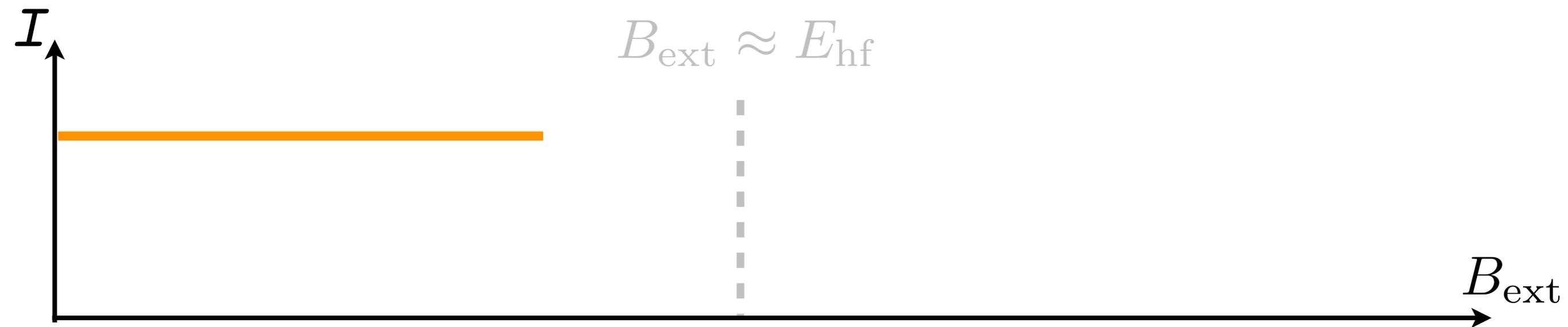
$$B_{\text{ext}} = 0$$



$$B_{\text{ext}} \gg E_{\text{hf}}$$



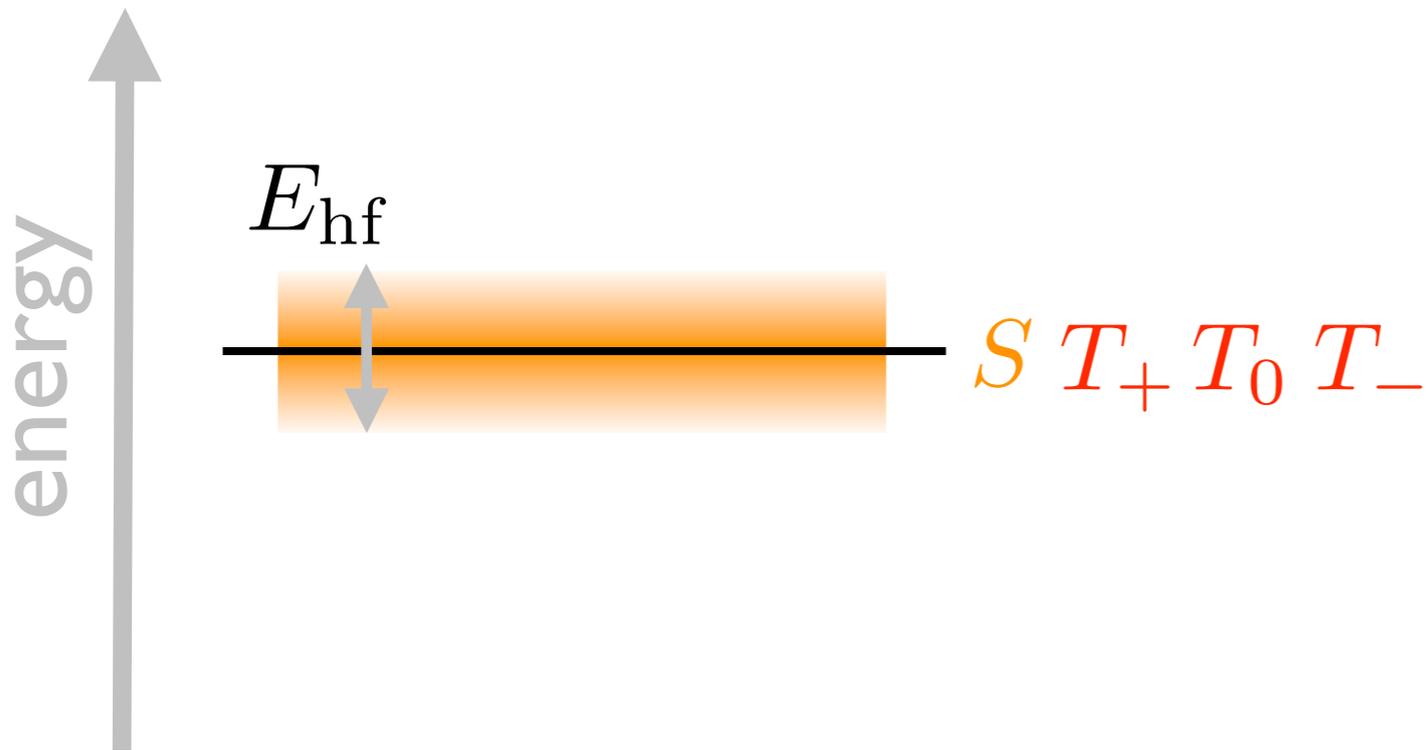
$$B_{\text{ext}} \approx E_{\text{hf}}$$



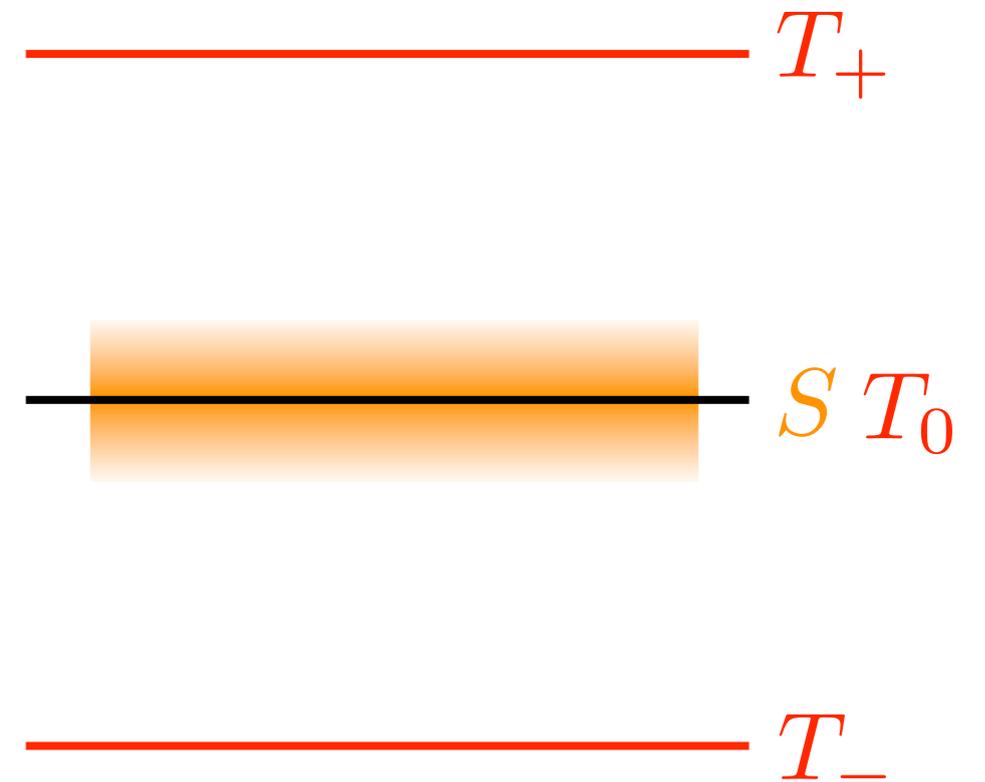
# Áram mágneses térben

## (1,1) energiaszintek

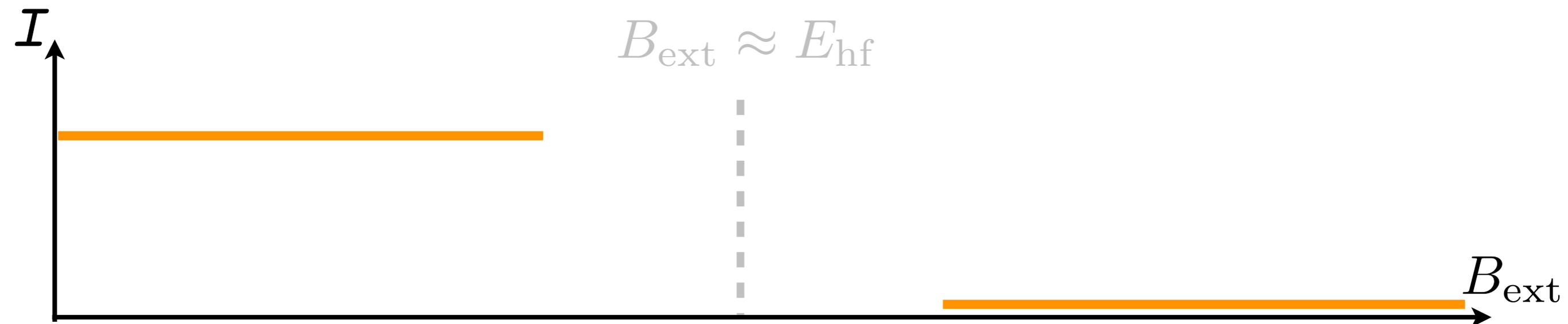
$$B_{\text{ext}} = 0$$



$$B_{\text{ext}} \gg E_{\text{hf}}$$



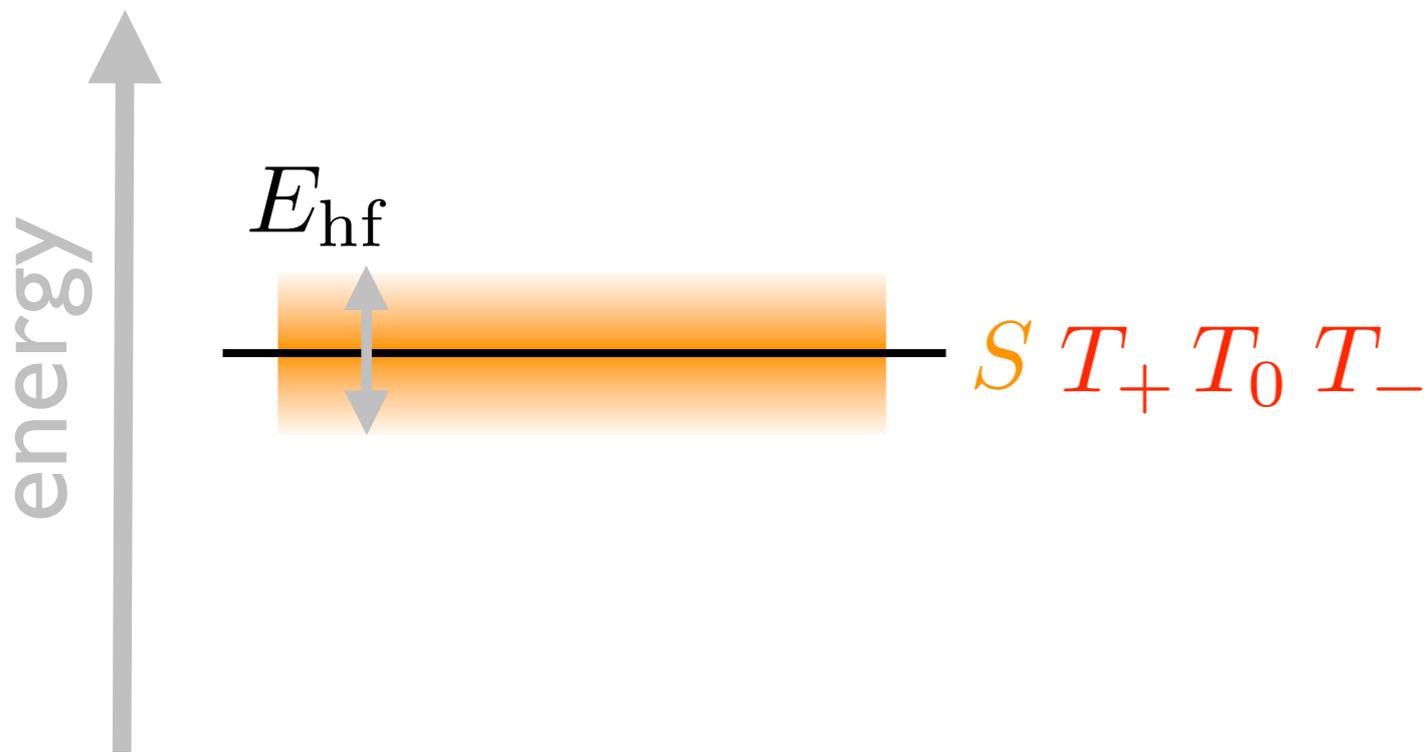
$$B_{\text{ext}} \approx E_{\text{hf}}$$



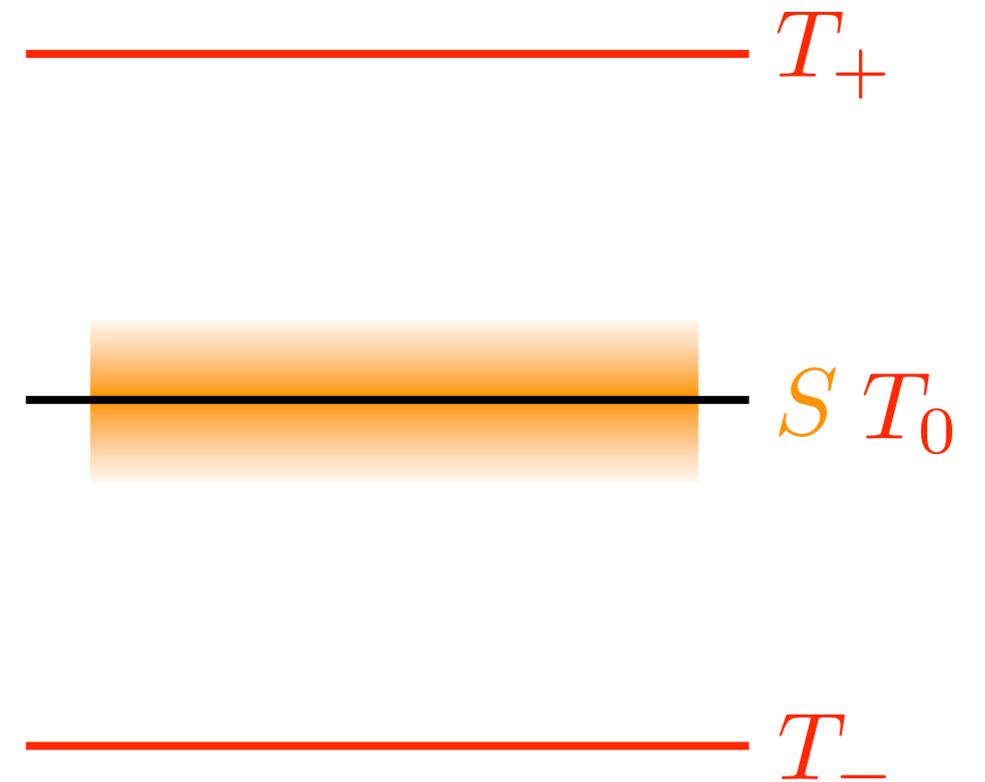
# Áram mágneses térben

## (1,1) energiaszintek

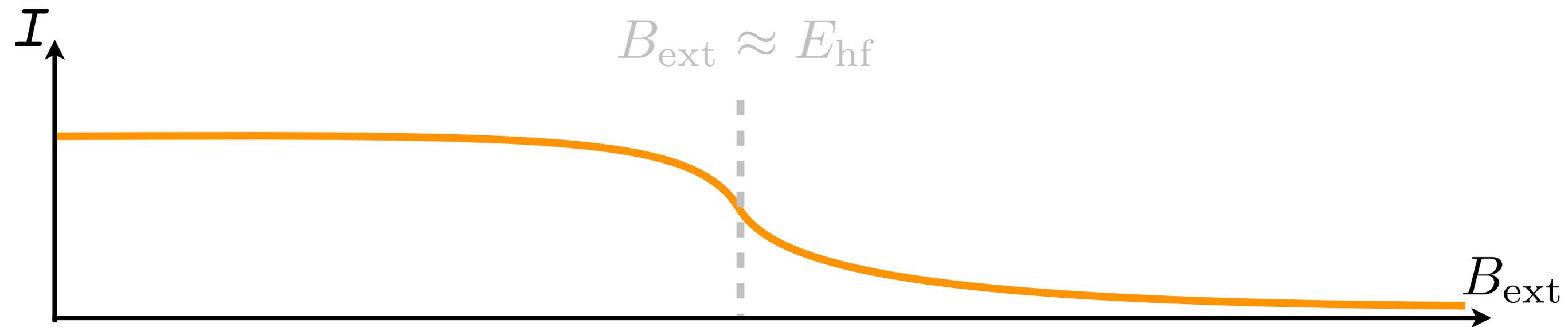
$$B_{\text{ext}} = 0$$

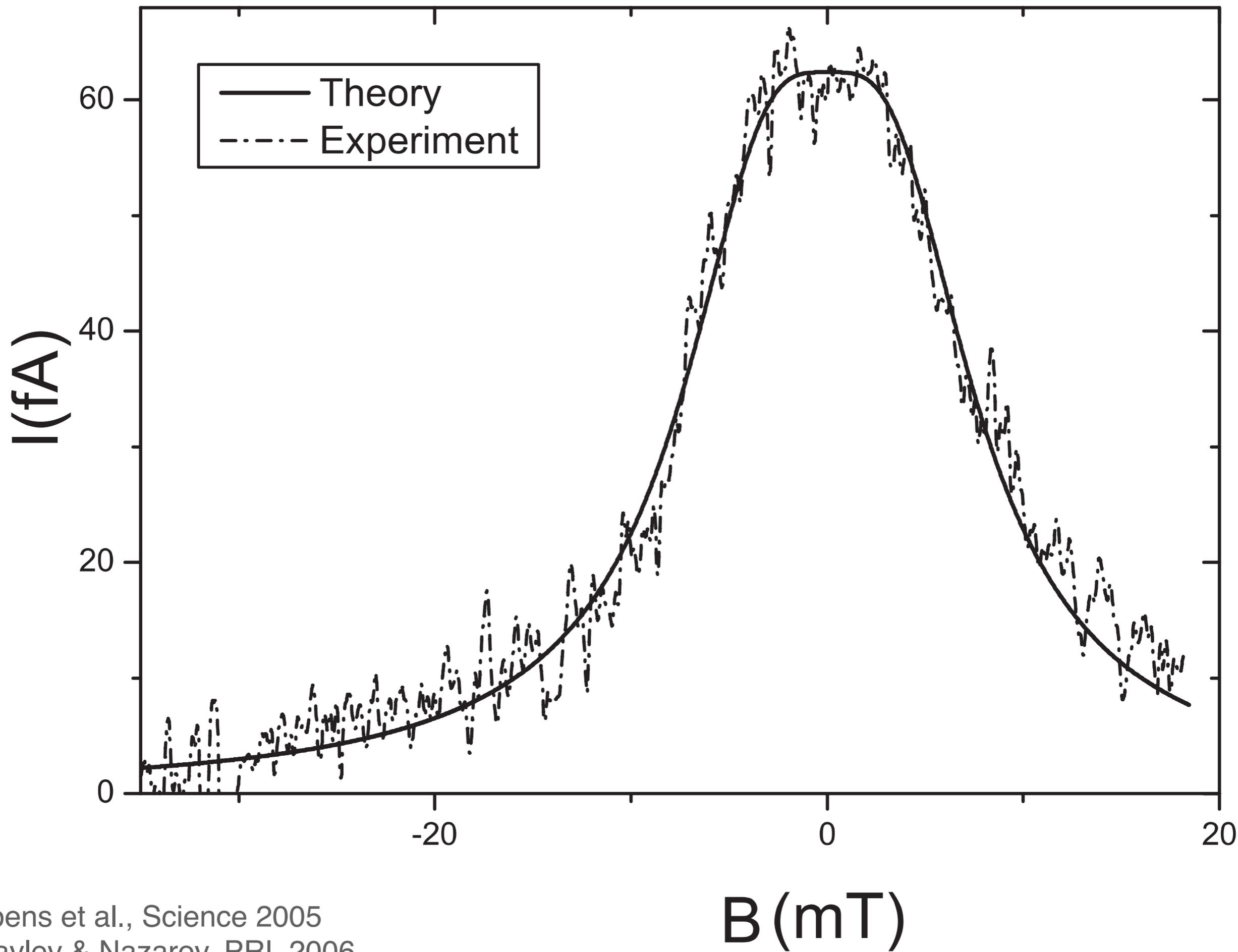


$$B_{\text{ext}} \gg E_{\text{hf}}$$



$$B_{\text{ext}} \approx E_{\text{hf}}$$

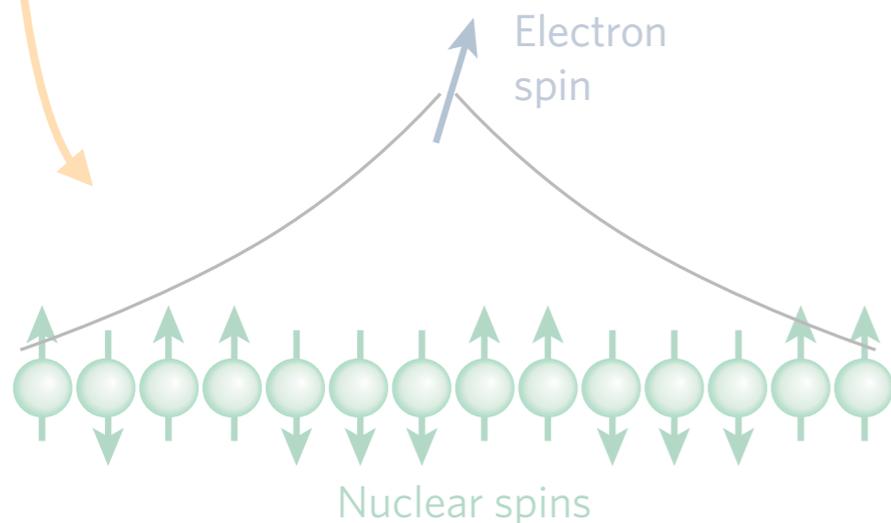




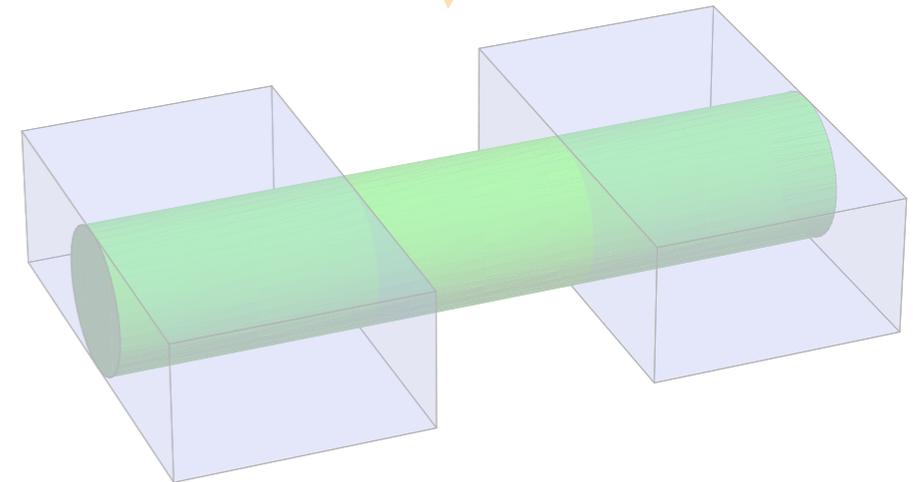
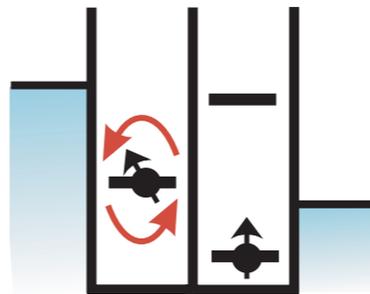
# Tartalom

(Spinblokádkettős kvantumdotokban)

- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok

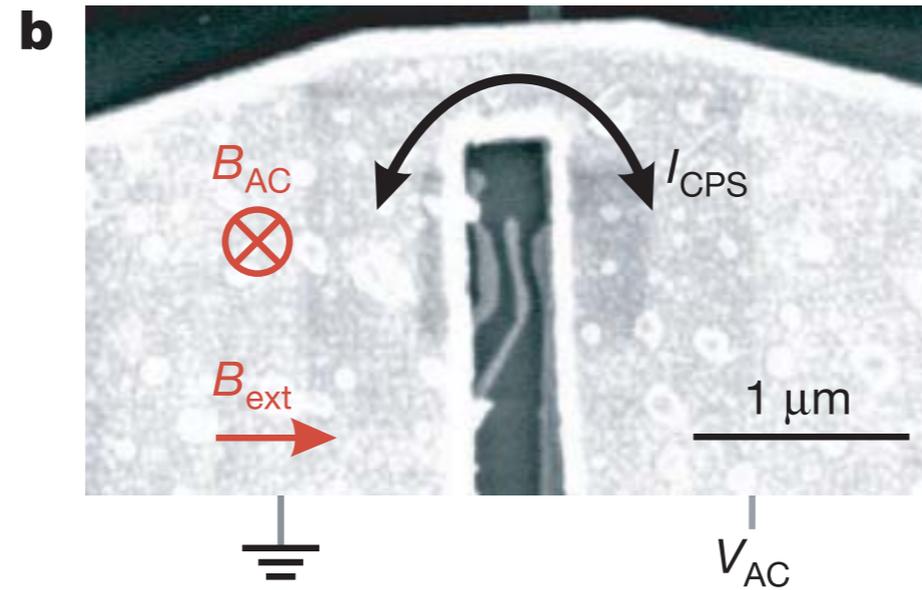
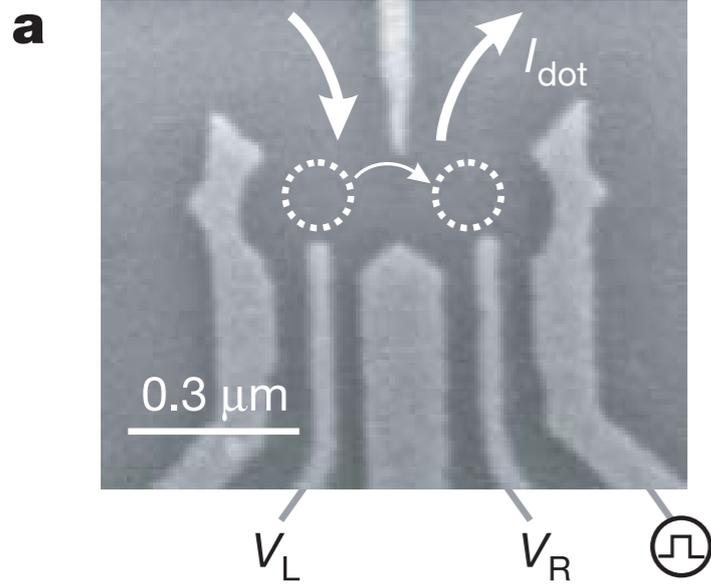


Spin  
manipulation



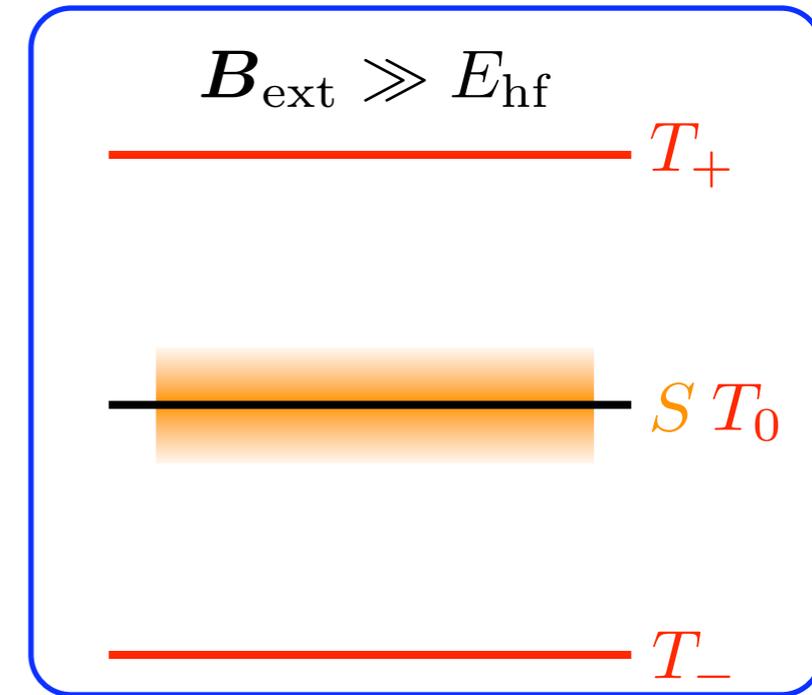
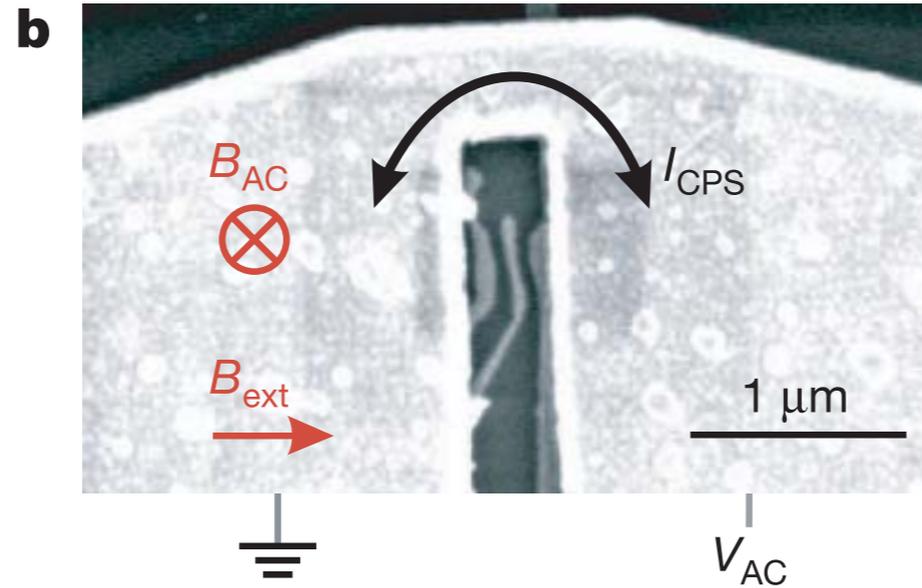
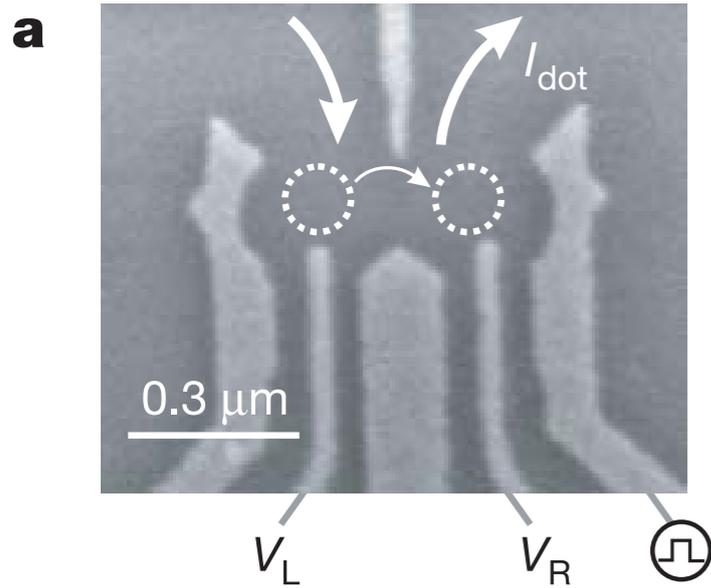
# Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006



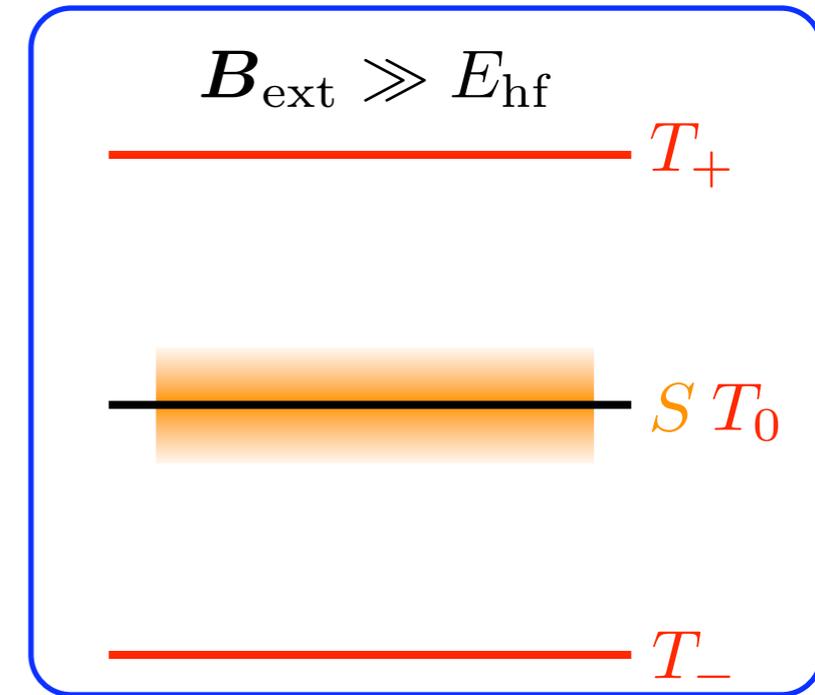
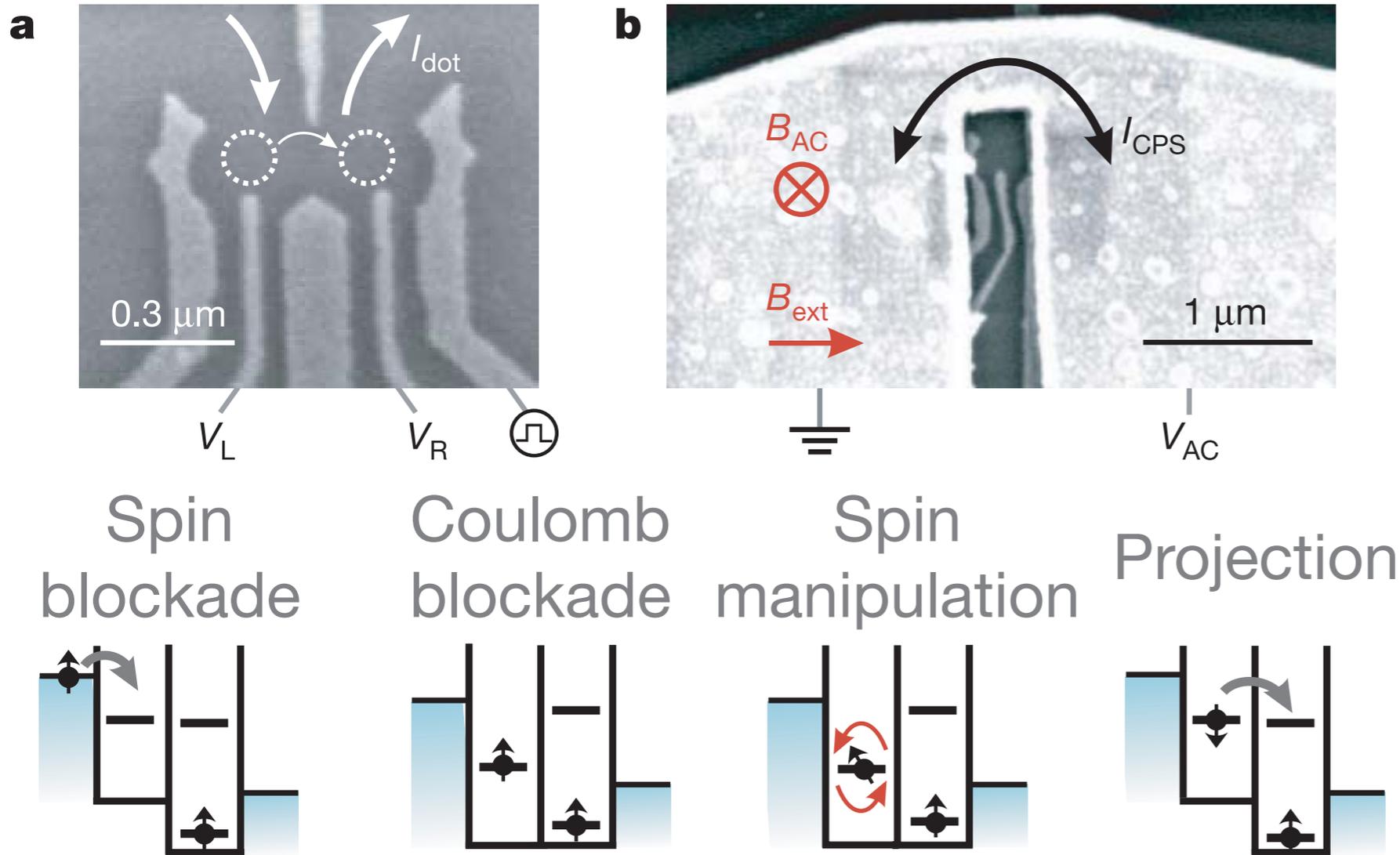
# Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006



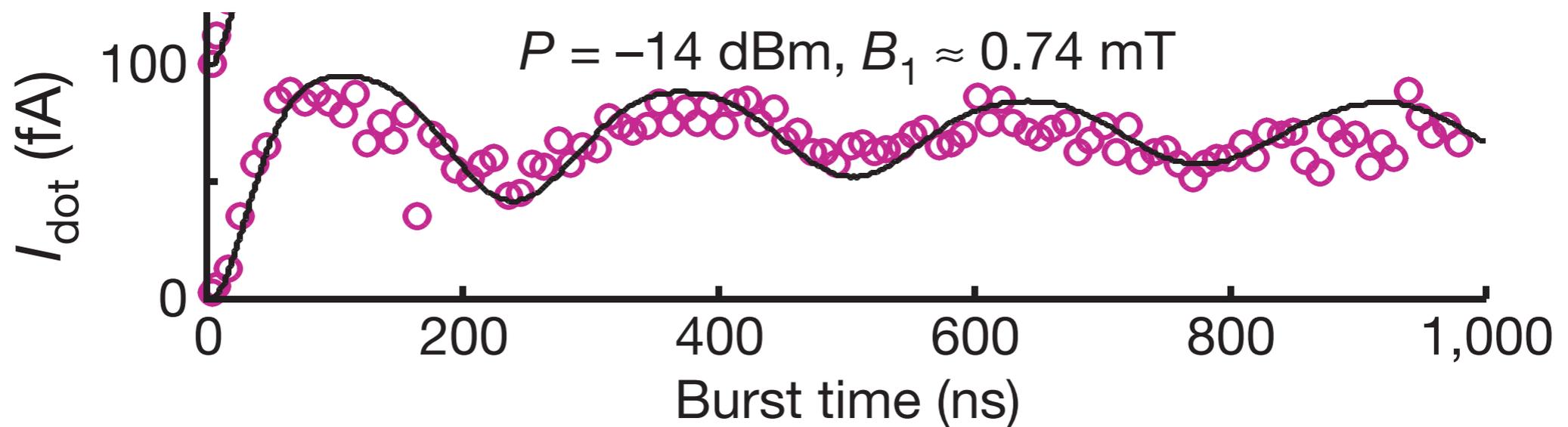
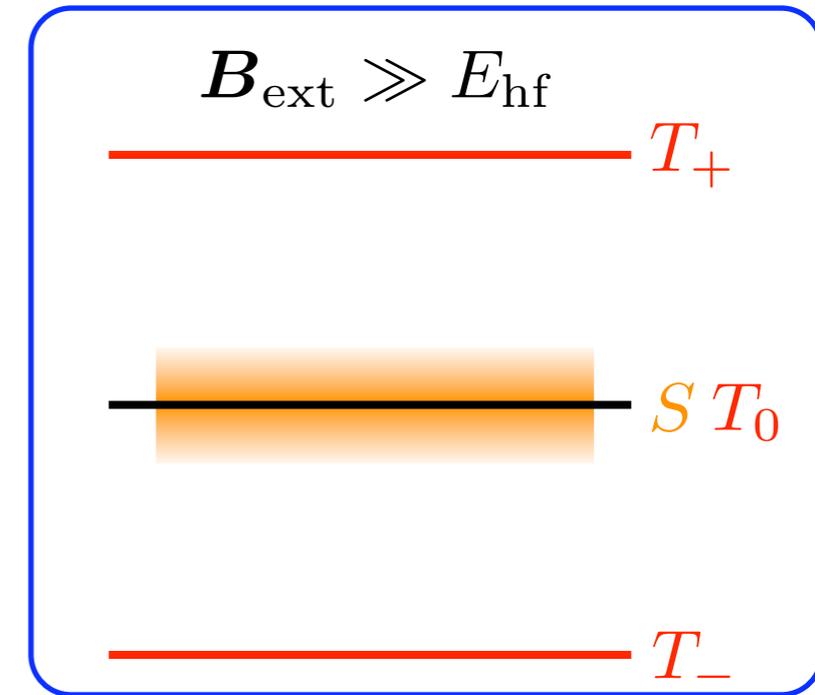
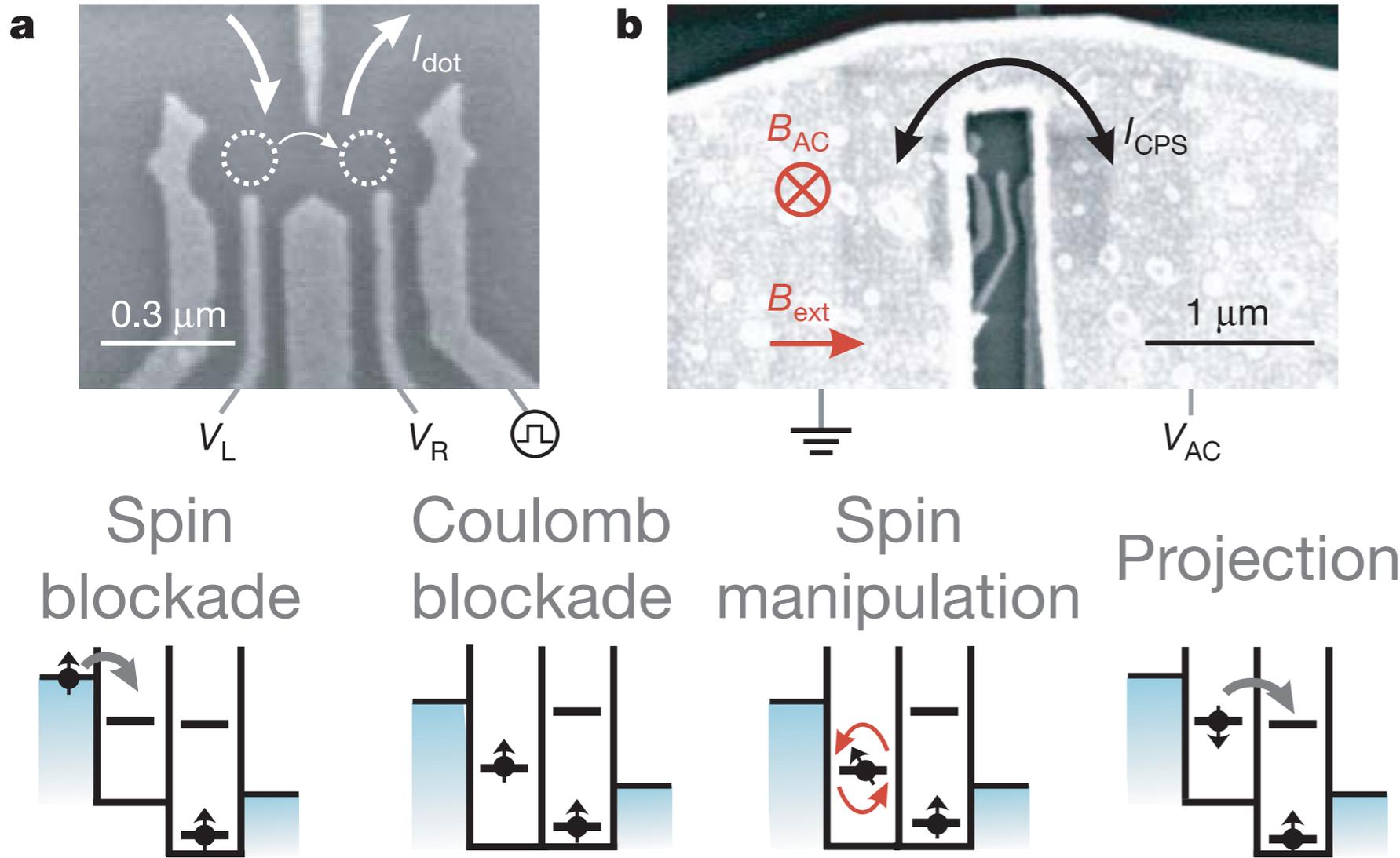
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Koppens et al., Nature 2006



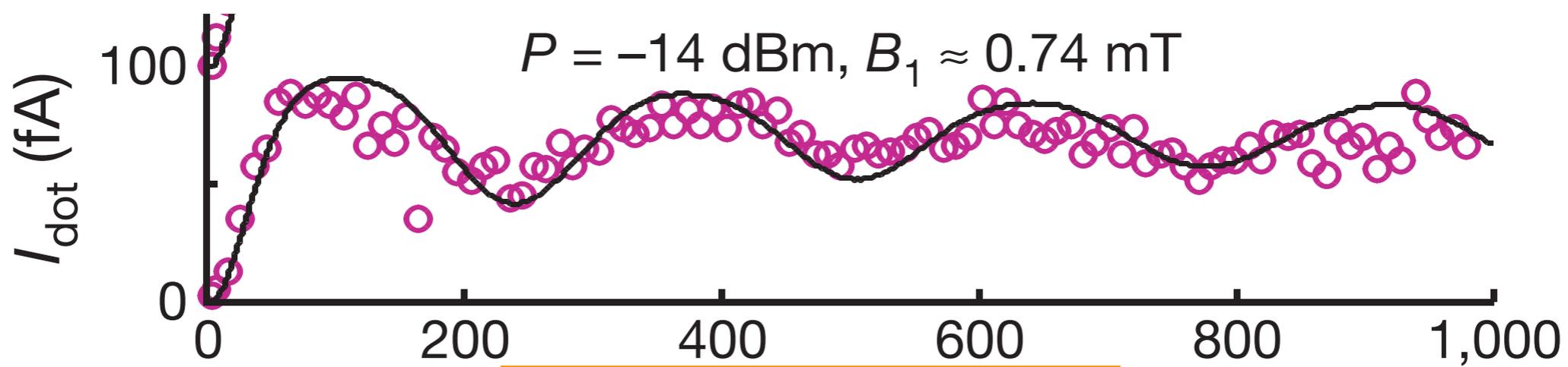
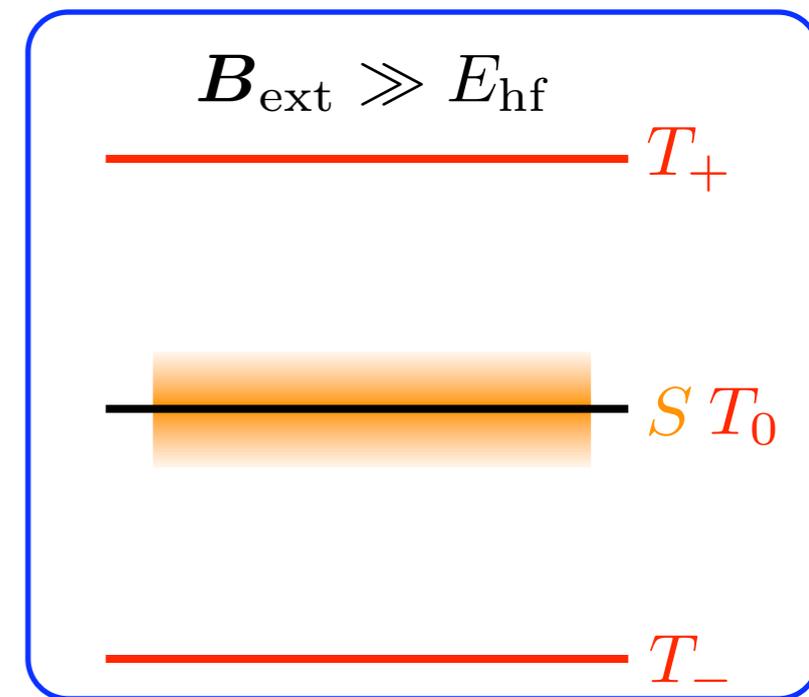
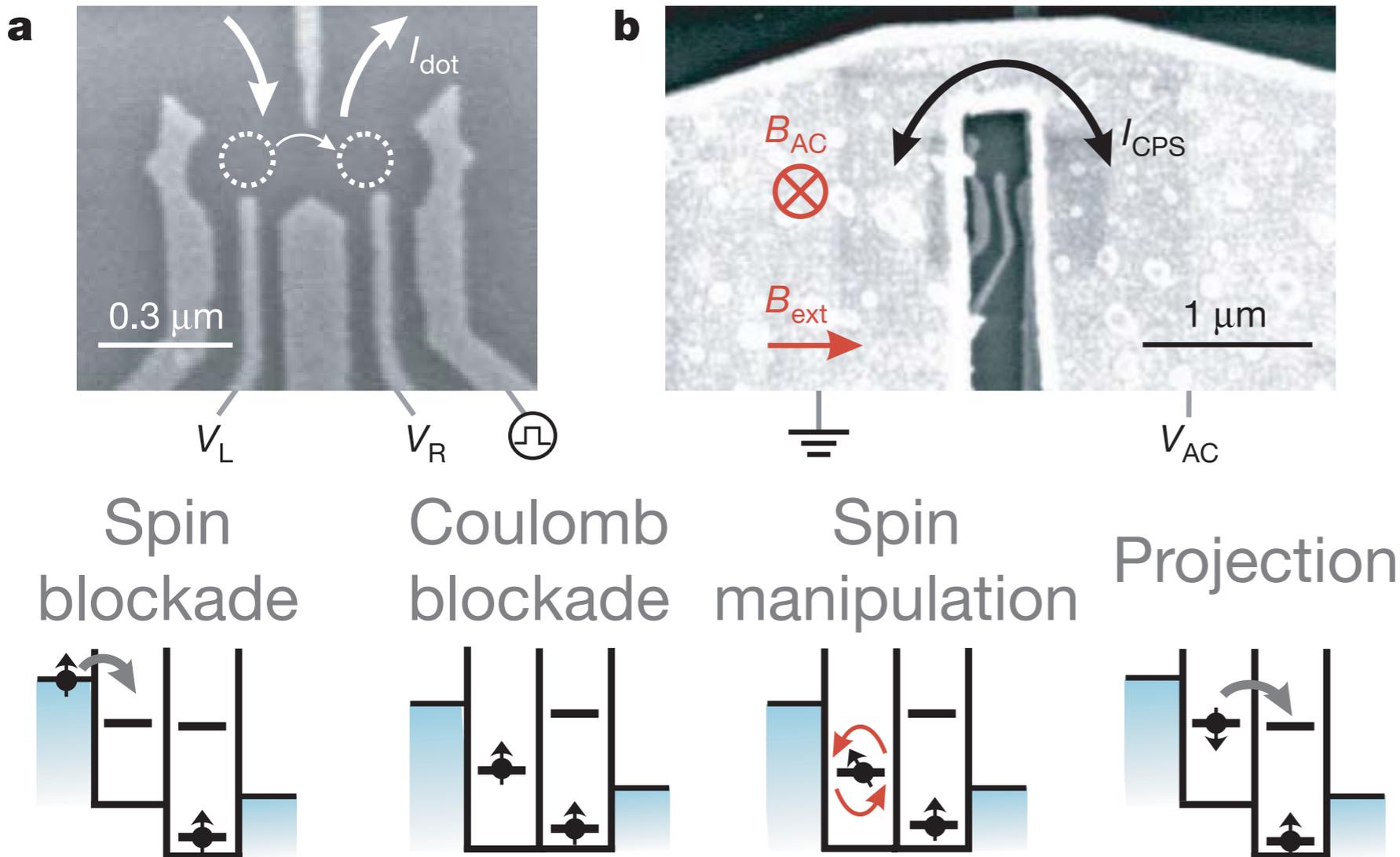
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Koppens et al., Nature 2006



# Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006

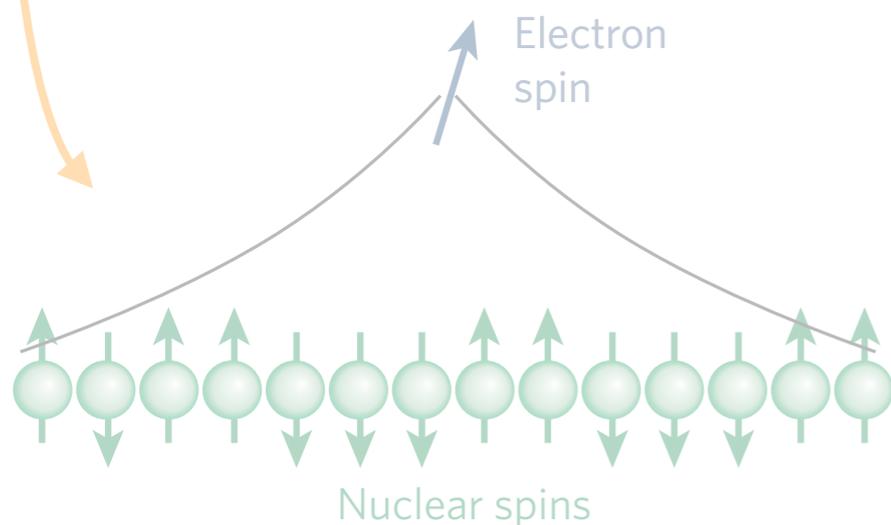


~ spinforgatás szöge

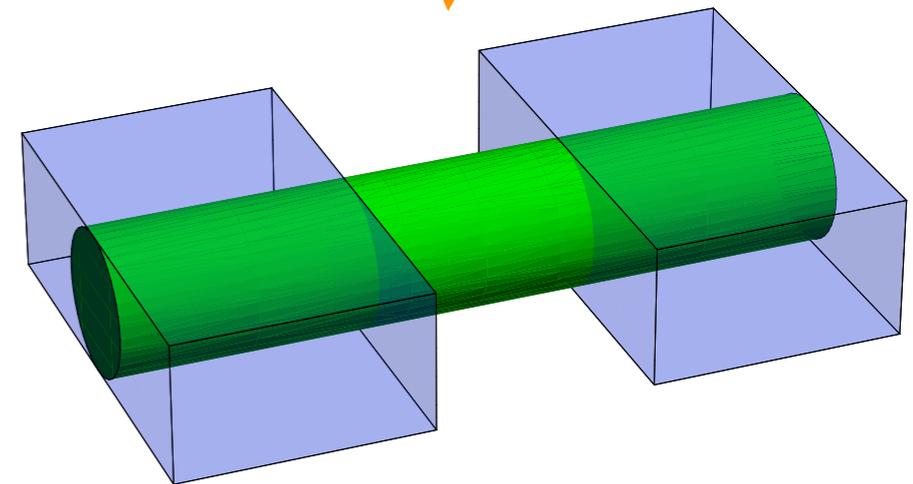
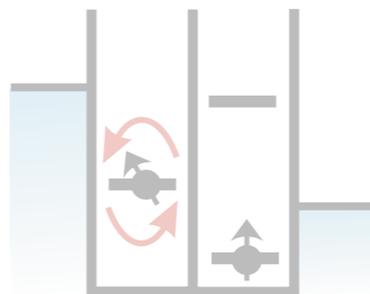
# Tartalom

(Spinblokádkettős kvantumdotokban)

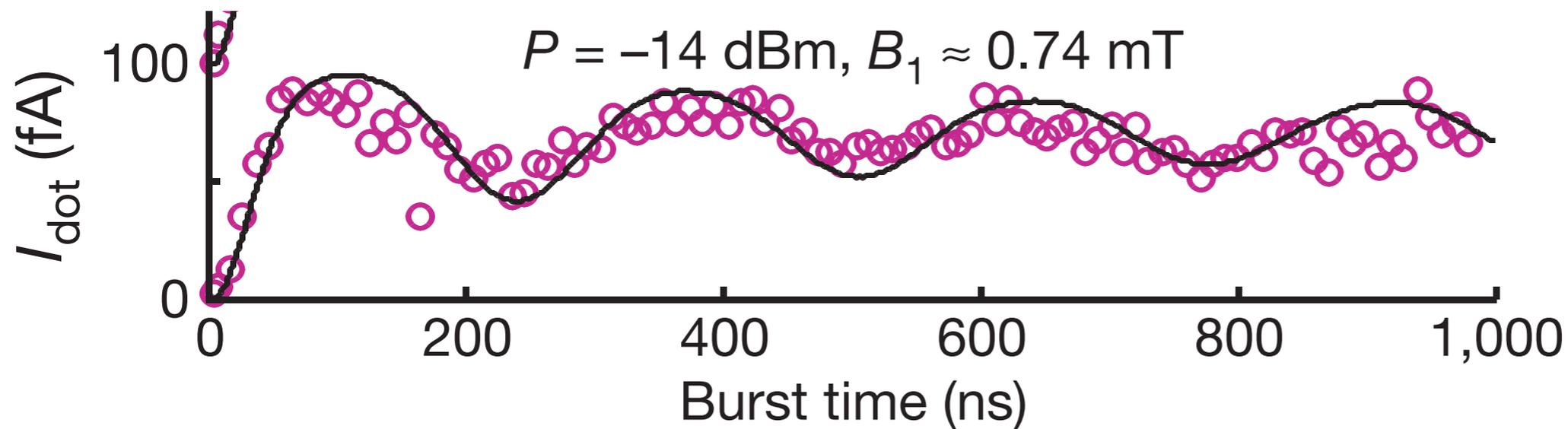
- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok



Spin  
manipulation



# Szén-alapú kvantumdotok - Motiváció



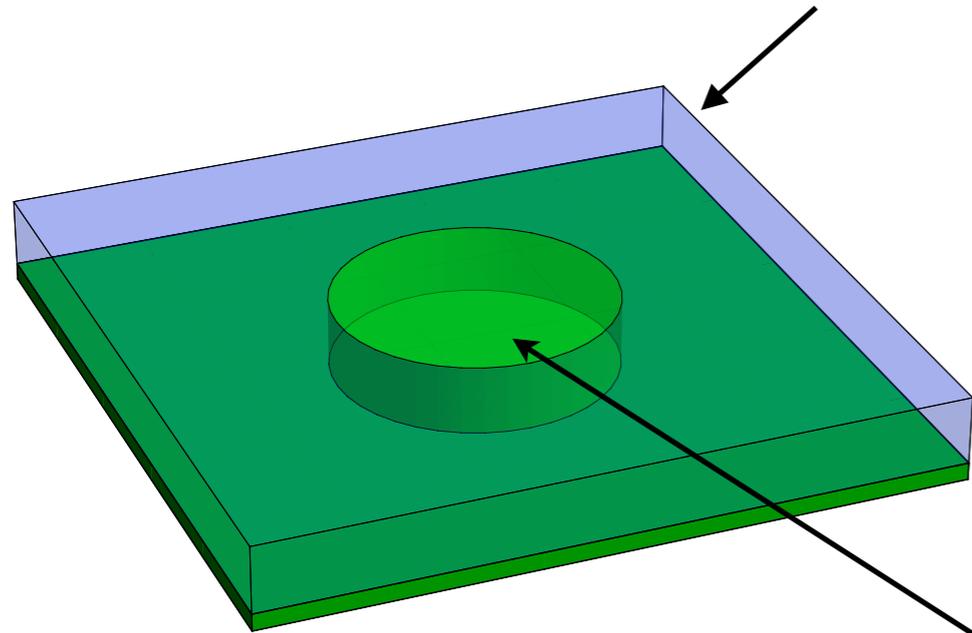
dekoherencia:  
véletlen magspin-konfigurációk

## Stratégiák a dekoherenciával szemben

- 1) magspinek kontrollja
- 2) zérus magspinű anyagok (C, Si, Ge)

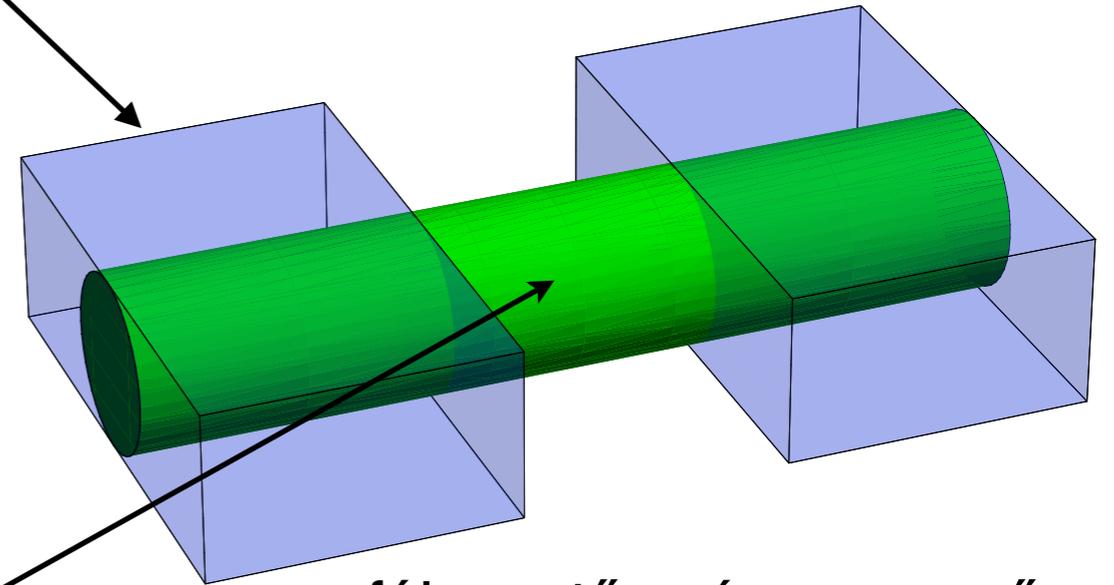
# Szén-alapú kvantumdotok

elektrosztatikus potenciálgát



grafén (tiltott sávval)

elmélet: Recher et al. PRB 2009

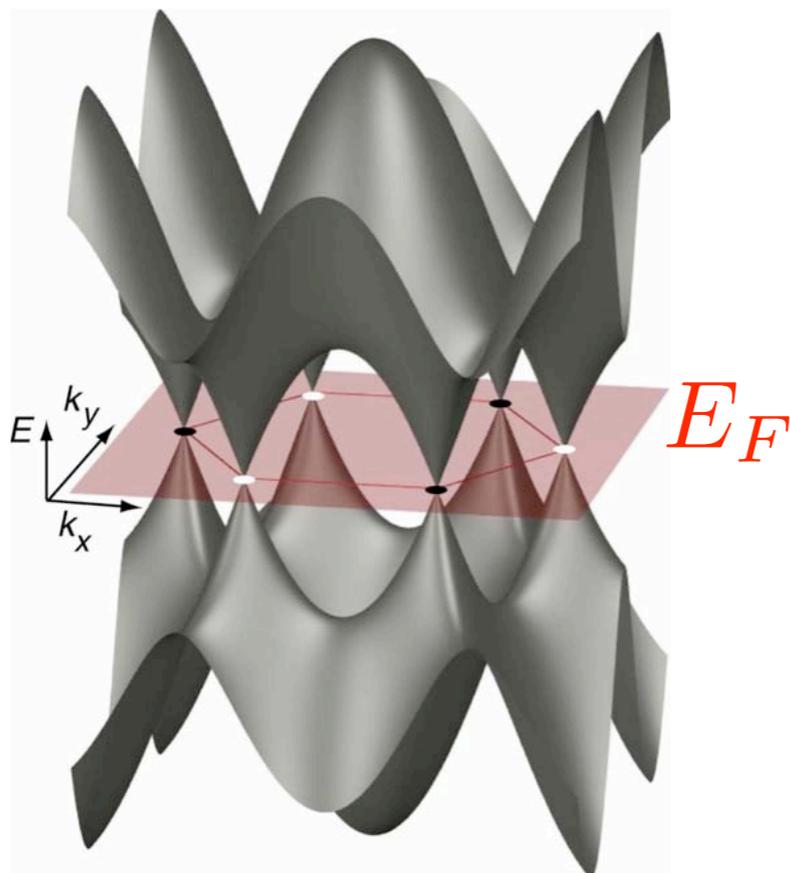


félvezető szén-nanocső

kísérlet: Cornell, Delft, Harvard, Basel,...

energiaszintek:

spin és „völgy” (valley) degeneráció



Melyik az optimális qubit?

- 1) spin?
- 2) valley?
- 3) a kettő kombinációja?