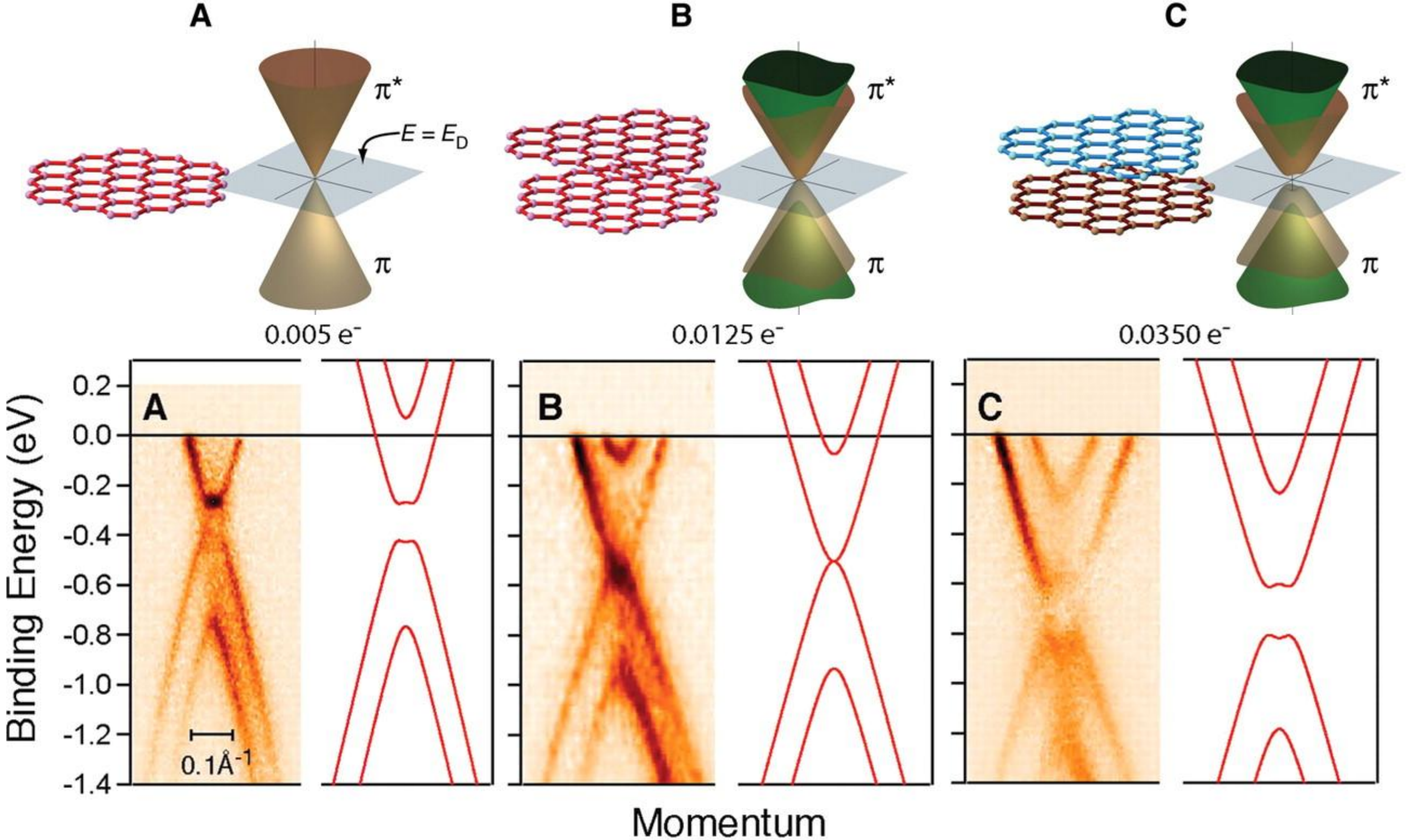
Szimmetriasértés kétrétegű grafénben

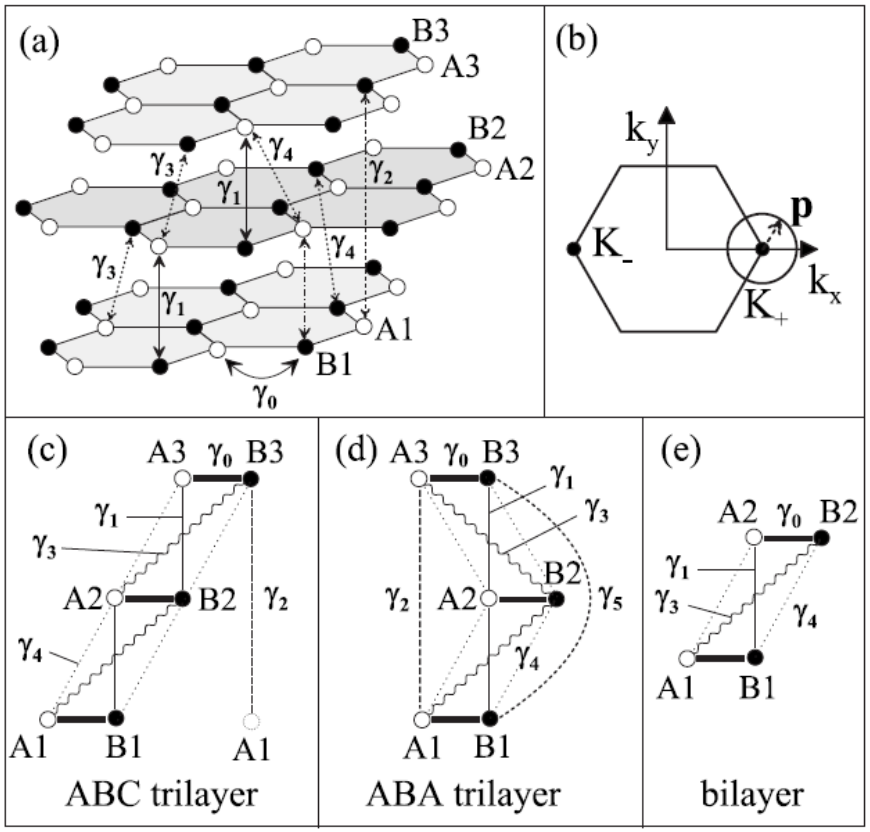
BME nanoszeminárium

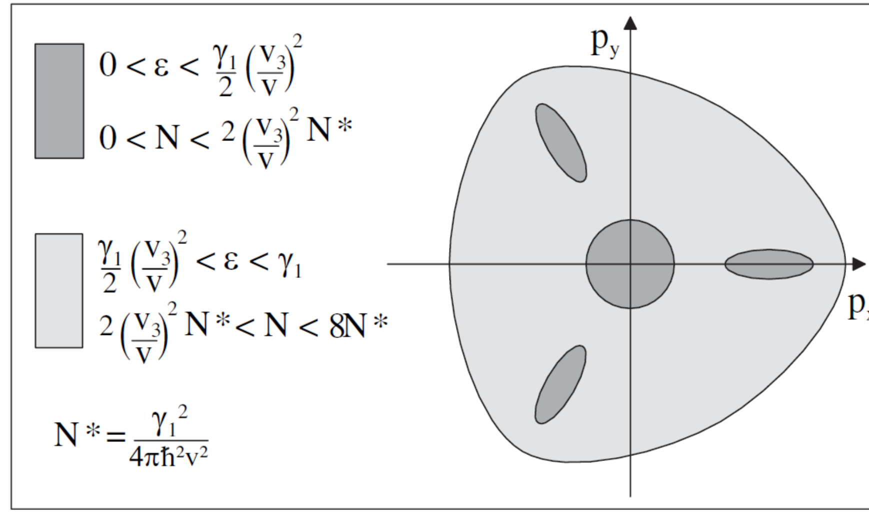
Kétrétegű grafén gyorstalpaló

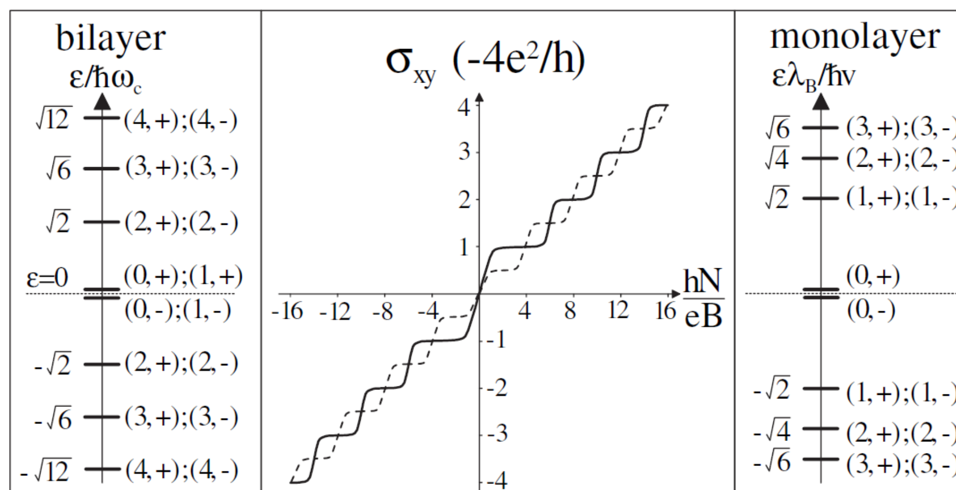


T Ohta et al. Science 2006;313:951-954

Kétrétegű grafén gyorstalpaló







Phys. Rev. Lett **96**, 086805 (2006)

[redacted]

PHYSICAL REVIEW B **82**, 201408(R) (2010)

Spontaneous symmetry breaking and Lifshitz transition in bilayer graphene

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We derive the renormalization-group equations describing all the short-range interactions in bilayer graphene allowed by symmetry, the long-range Coulomb interaction, and band-structure parameters. For certain range of parameters, we predict the first-order phase transition to the uniaxially deformed gapless state accompanied by the change in the topology of the electron spectrum.

[redacted]

PHYSICAL REVIEW B **84**, 041404(R) (2011)

Strained bilayer graphene: Band structure topology and Landau level spectrum

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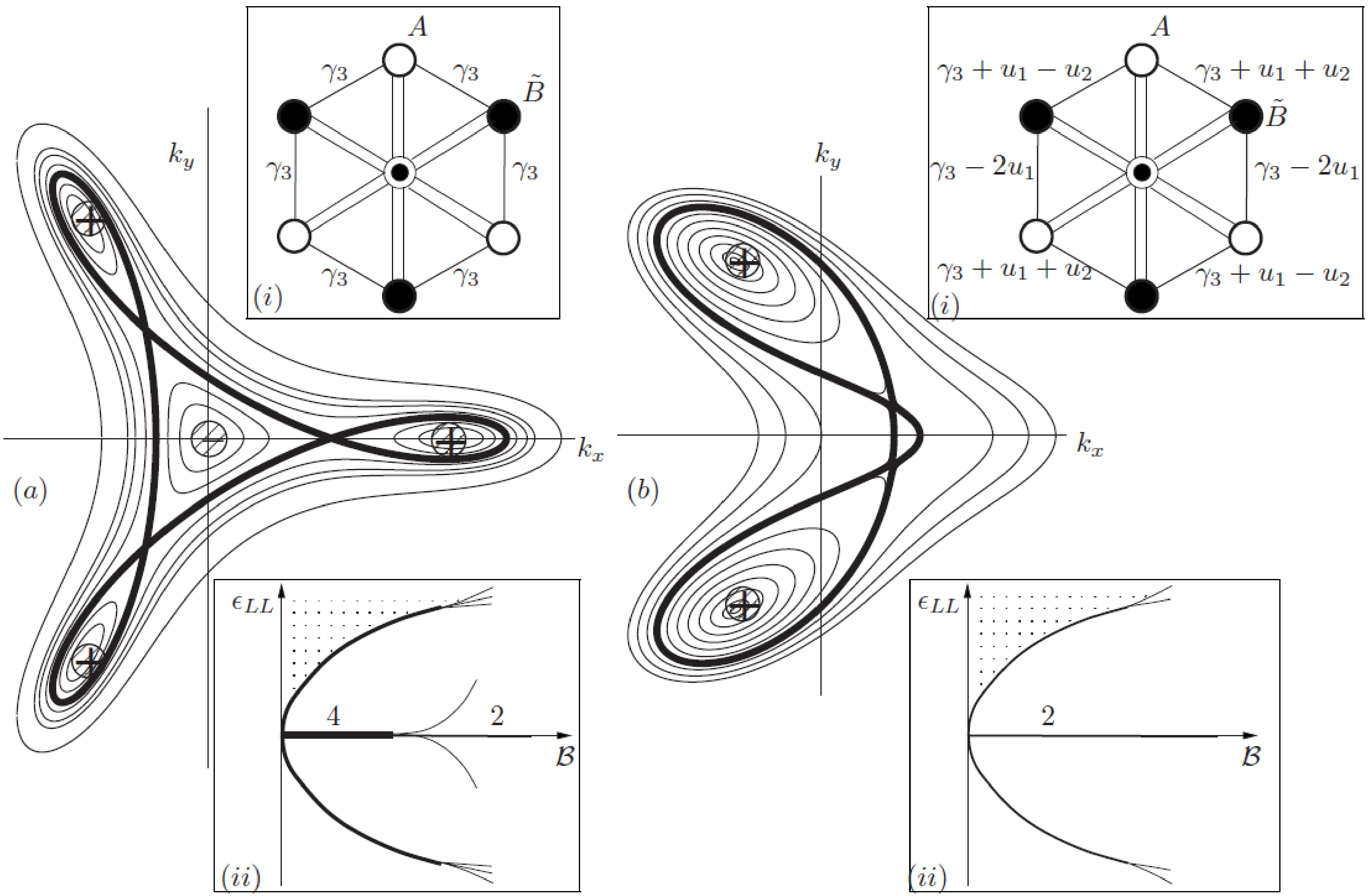
We show that topology of the low-energy band structure in bilayer graphene critically depends on mechanical deformations of the crystal which may easily develop in suspended graphene flakes. We describe the Lifshitz transition that takes place in strained bilayers upon splitting the parabolic bands at intermediate energies into several Dirac cones at the energy scale of a few meV. Then, we show how this affects the electron Landau level spectra and the quantum Hall effect.



A
γ_3
γ_3
$\tilde{B}$
γ_3
γ_3
γ_3
γ_3
(i)
k_y
k_x
(a)
ϵ_{LL}
4
2
$\mathcal{B}$
(ii)
A
$\gamma_3 + u_1 - u_2$
$\gamma_3 + u_1 + u_2$
$\tilde{B}$
$\gamma_3 - 2u_1$
$\gamma_3 - 2u_1$
$\gamma_3 + u_1 + u_2$
$\gamma_3 + u_1 - u_2$
(i)
k_y
k_x
(b)
ϵ_{LL}
2
$\mathcal{B}$
(ii)

A Hamilton-operátor

$$\hat{\mathcal{H}} = \int d^2\mathbf{r}\Psi^\dagger_\sigma[\hat{h}_0 + \hat{h}_w + \hat{h}_c + \hat{h}_{sr}]\Psi_\sigma.$$

Bázis definició

$$\Psi_\sigma = (\hat{\psi}^{A,K}_\sigma, \hat{\psi}^{\tilde{B},K}_\sigma; \hat{\psi}^{\tilde{B},K'}_\sigma, -\hat{\psi}^{A,K'}_\sigma) \qquad \hat{M}^j_i \equiv \hat{\tau}^{KK'}_i \otimes \hat{\tau}^{A\tilde{B}}_j$$

$$\hat{h}_0(k_{x,y}) = -[\hat{M}^1_3(k_x^2 - k_y^2) - 2\hat{M}^2_3 k_x k_y]/(2m). \quad \hat{h}_w(k_{x,y}) = v_3[\hat{M}^1_0 k_x + \hat{M}^2_0 k_y]$$

Nemkölcsönható bilayer
Dimer redukció után

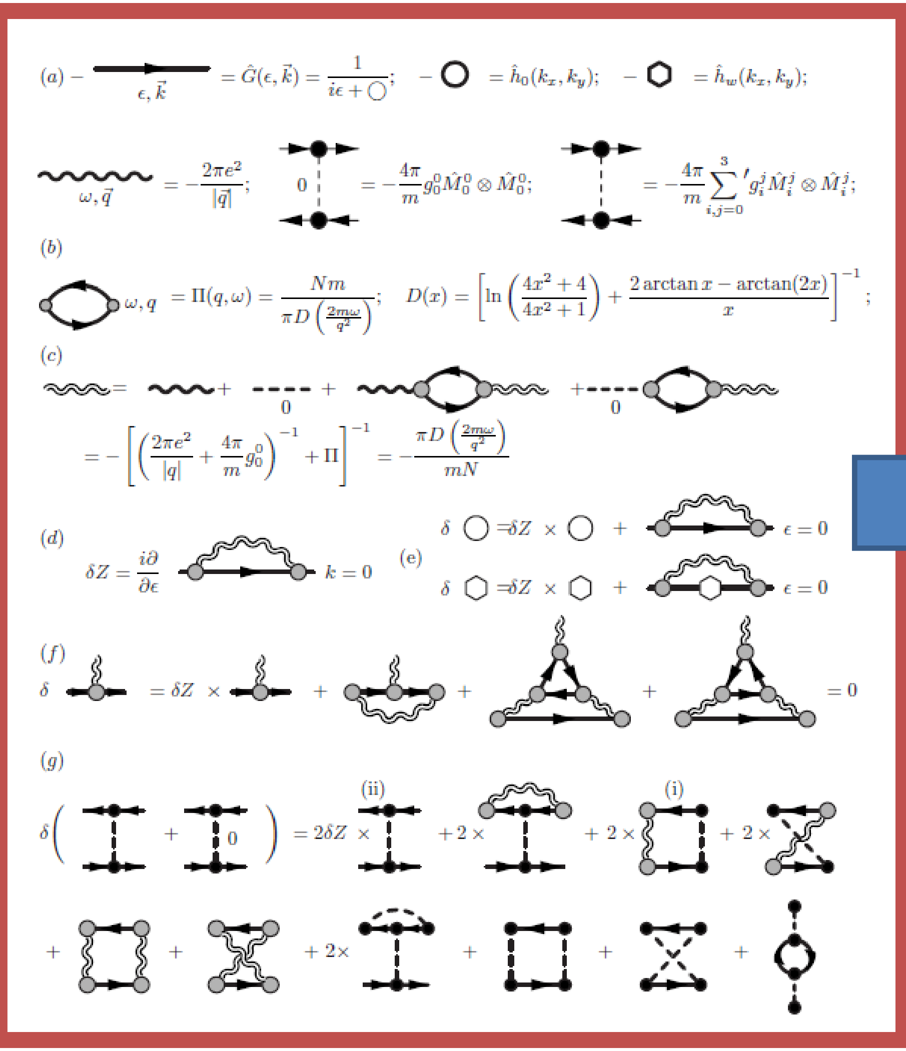
Coulomb

egyszerű →

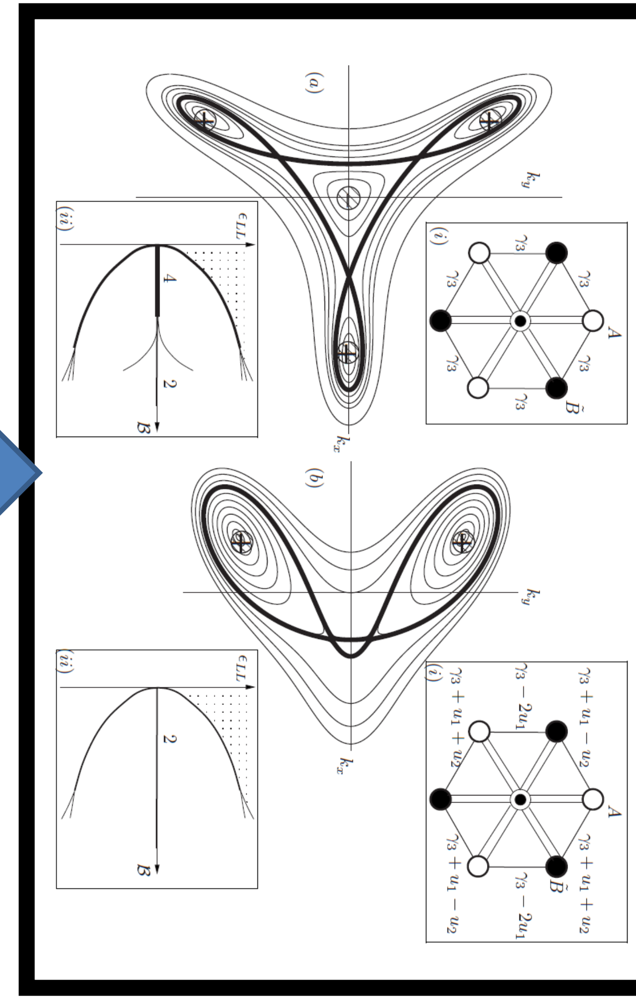
$$\hat{h}_c = \frac{e^2}{2}\int \frac{d^2\mathbf{r}'\Psi^\dagger_{\sigma'}(\mathbf{r}')\Psi_{\sigma'}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

$$\hat{h}_{sr} = (2\pi/m)\sum_{i,j=0}^{3} g^j_i \hat{M}^j_i[\Psi^\dagger \hat{M}^j_i \Psi]$$

← Bázis redukció miatt fellépő extra tag



RG+1*RUSSIAN



Falko: Ha a részecske sűrűség kicsi(~Dirac pont közelében van a Fermi-energia) úgy néz ki a gerjesztési spektrum a szimmetria sértett lesz! A gerjesztések élettartamát e-ph határozza meg.

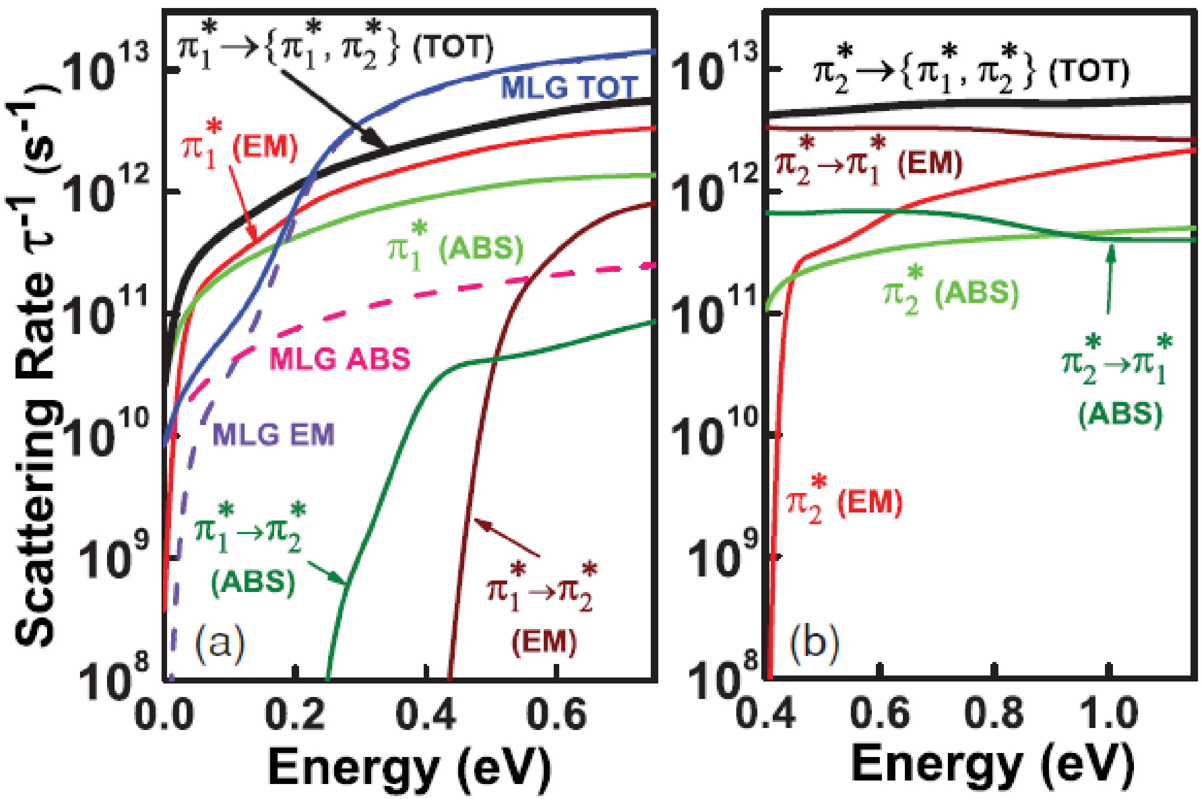
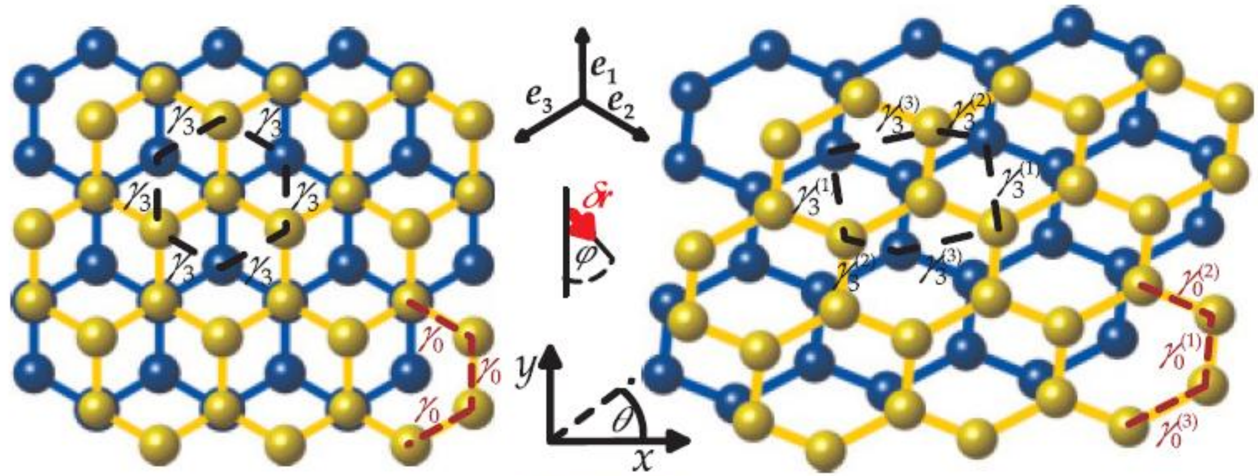
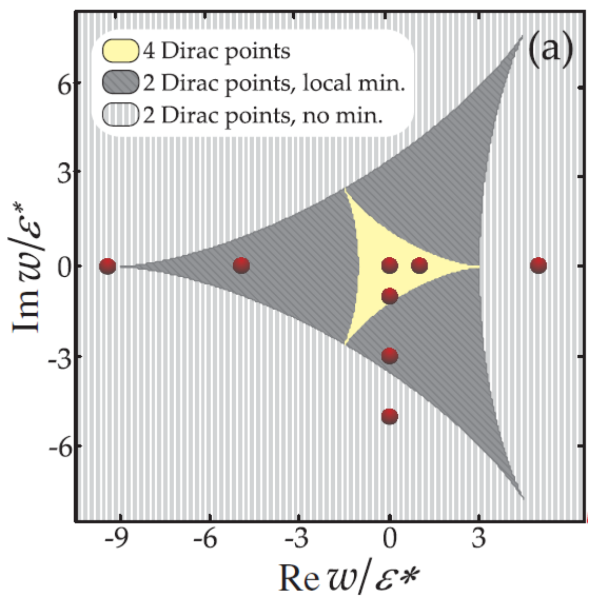


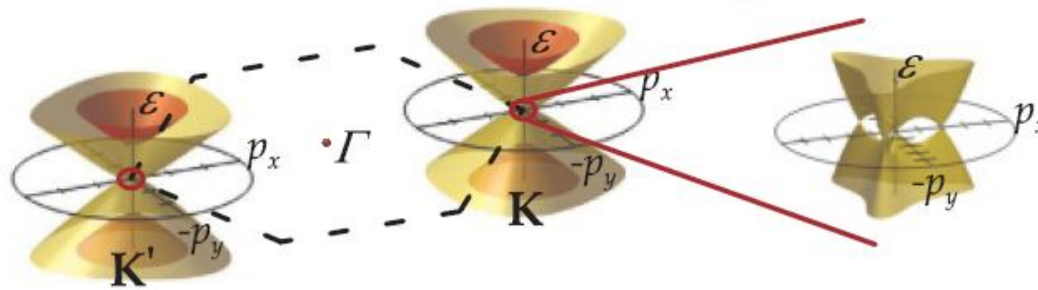
FIG. 4. (Color online) Electron-phonon scattering rates in BLG at $T = 300$ K as a function of electron energy. The initial electron state is in the (a) π_1^* and (b) π_2^* conduction bands, respectively. Both intra- (π_i^*) and interband ($\pi_i^* \to \pi_j^*$) transitions are considered. The π_1^*-π_2^* band offset is 0.4 eV. ABS (EM) stands for phonon absorption (emission). TOT represents the sum of all possible interactions. In (a), the corresponding results for MLG are also plotted for comparison (Ref. 8). The reference for energy (zero) is set at the bottom of the π_1^* band.

Phys. Rev **B** 83 161402(R) (2011)

Mechanikai deformáció hatása







$$\hat{\boldsymbol{H}} = -\frac{1}{2m}\begin{pmatrix} 0 & (\tilde{\boldsymbol{\pi}}^{\dagger})^2 \\ \tilde{\boldsymbol{\pi}}^2 & 0 \end{pmatrix} + \xi v_3 \begin{pmatrix} 0 & \tilde{\boldsymbol{\pi}} \\ \tilde{\boldsymbol{\pi}}^{\dagger} & 0 \end{pmatrix} + \begin{pmatrix} 0 & w \\ w^* & 0 \end{pmatrix},$$

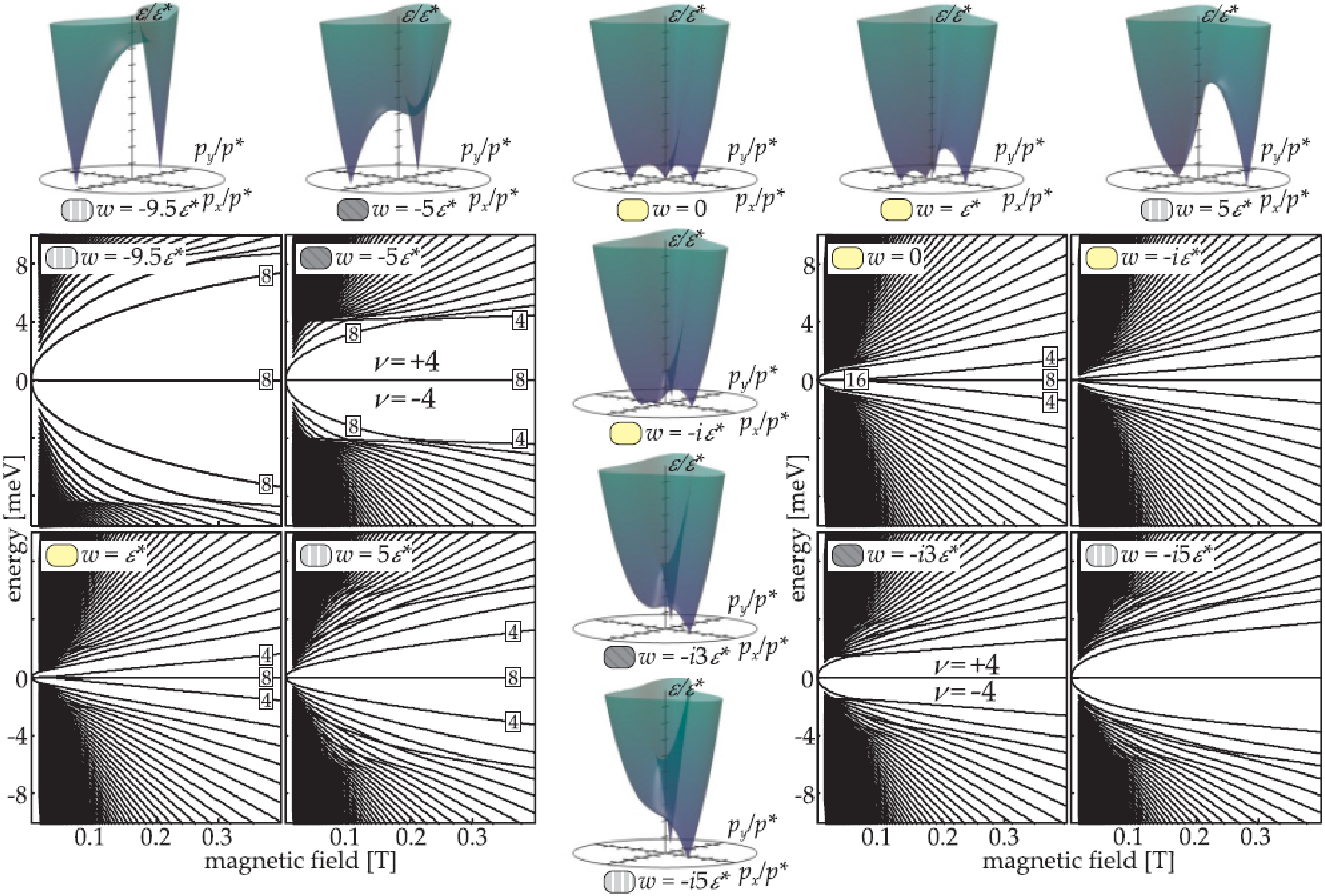
$$w = \mathcal{A}_3 - \frac{\gamma_3}{\gamma_0}\mathcal{A}_0, \quad \eta_{0/3} = \frac{d \ln \gamma_{0/3}}{d \ln r_{AB}},$$

$$\mathcal{A}_0 = \frac{3}{4}(\delta - \delta')e^{-2i\theta}\gamma_0\eta_0 \equiv \tilde{\mathcal{A}}_0 + (\partial_x + i\partial_y)\phi,$$

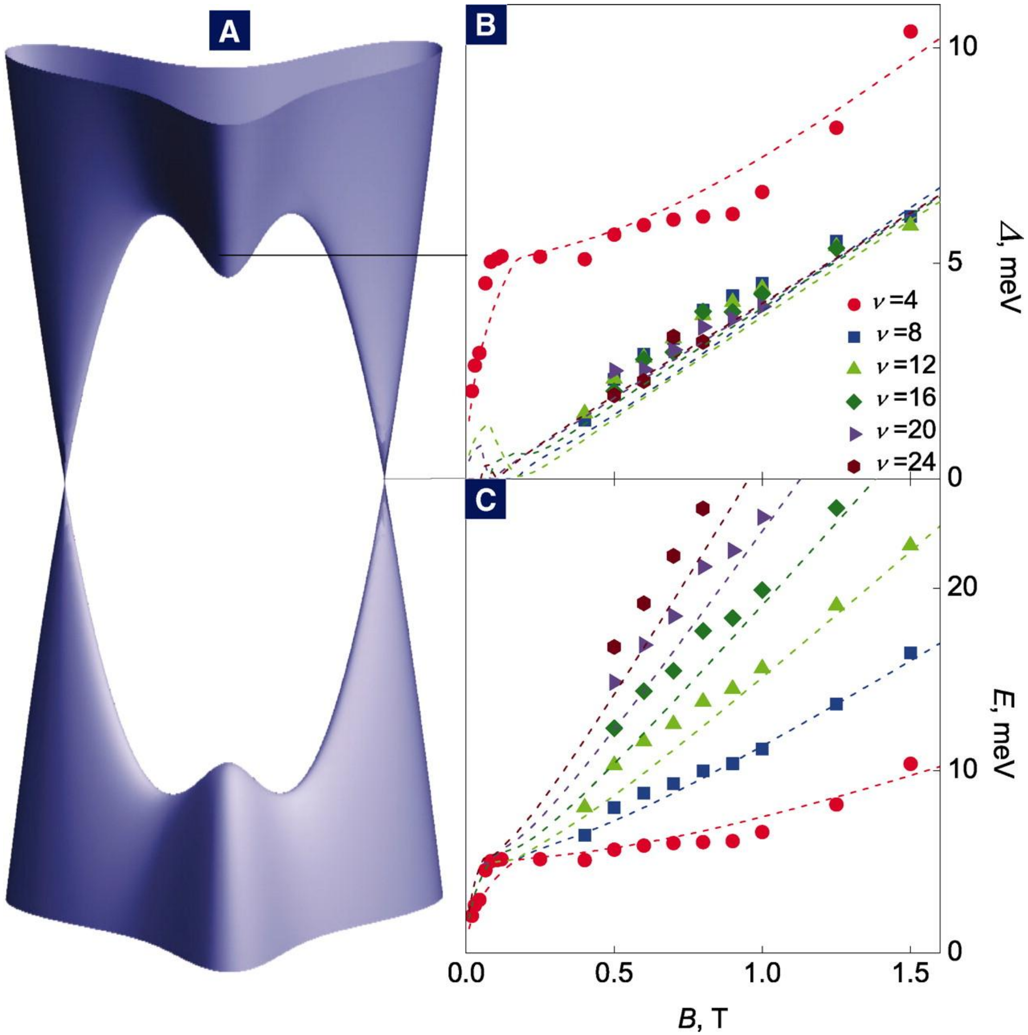
$$\mathcal{A}_3 = \frac{3}{4}(\delta - \delta')e^{-2i\theta}\gamma_3\eta_3 - \frac{3}{2}\frac{\delta r}{r_{AB}}e^{i\varphi}\gamma_3\eta_3,$$

$$\tilde{\boldsymbol{\pi}} = p_x + ip_y + \tilde{\mathcal{A}}_0, \quad \partial_x \mathrm{Im}\,\tilde{\mathcal{A}}_0 - \partial_y \mathrm{Re}\,\tilde{\mathcal{A}}_0 \equiv b_{\mathrm{eff}},$$

Mágneses tér



Low-energy electron spectrum for graphene bilayer, reconstructed due to nematic phase transition.



A S Mayorov et al. Science 2011;333:860-863

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Effect of the band structure topology on the minimal conductivity for bilayer graphene with symmetry breaking

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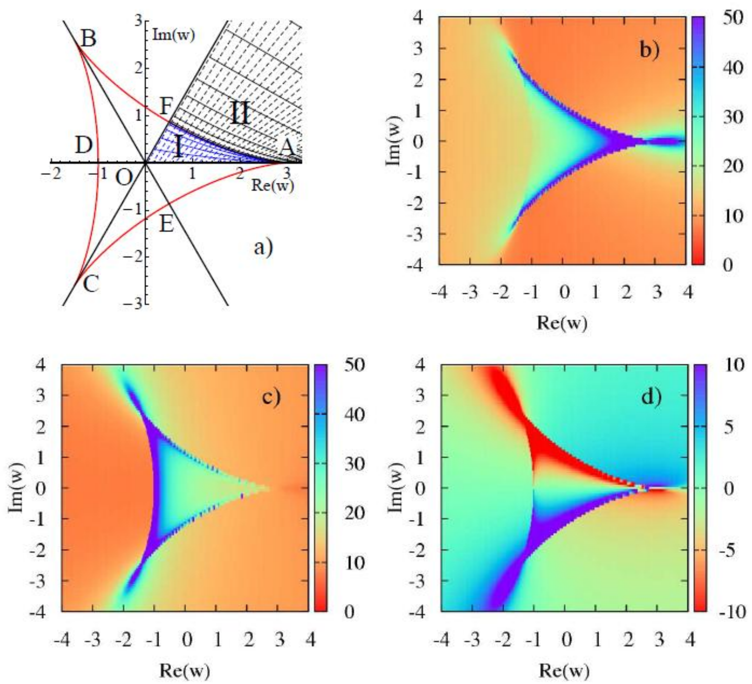
H-1117 Budapest, Pázmány Péter sétány 1/A, Hungary

Using the Kubo formula we develop a general and simple expression for the minimal conductivity in systems described by a two by two Hamiltonian. As an application we derive an analytical expression for the minimal conductivity tensor of bilayer graphene as a function of a complex parameter w related to recently proposed symmetry breaking mechanisms resulting from electron-electron interaction or strain applied to the sample. The number of Dirac points changes with varying parameter w, this directly affect the minimal conductivity. Our analytic expression is confirmed using an independent calculation based on Landauer approach and we find remarkably good agreement between the two methods. We demonstrate that the minimal conductivity is very sensitive to the change of the parameter w and the orientation of the electrodes with respect to the sample. Our results show that the minimal conductivity is closely related to the topology of the low energy band structure.

$$\sigma_{lm}^{\text{min}} = n_d \, \frac{2e^2}{h} \, \lim_{\eta \to 0} I_{lm}(\eta), \quad \text{where}$$

$$I_{lm}(\eta) = \eta^2 \int \frac{d^2\mathbf{k}}{(2\pi)^2} \, \mathrm{Tr}\, T_{lm}(\mathbf{k}, \eta),$$

$$T_{lm}(\mathbf{k}, \eta) = \left[\eta^2 + H^2(\mathbf{k})\right]^{-1} \frac{\partial H(\mathbf{k})}{\partial k_l} \times \left[\eta^2 + H^2(\mathbf{k})\right]^{-1} \frac{\partial H(\mathbf{k})}{\partial k_m},$$



DGY+pince étlen szomjan=Parametrizálás

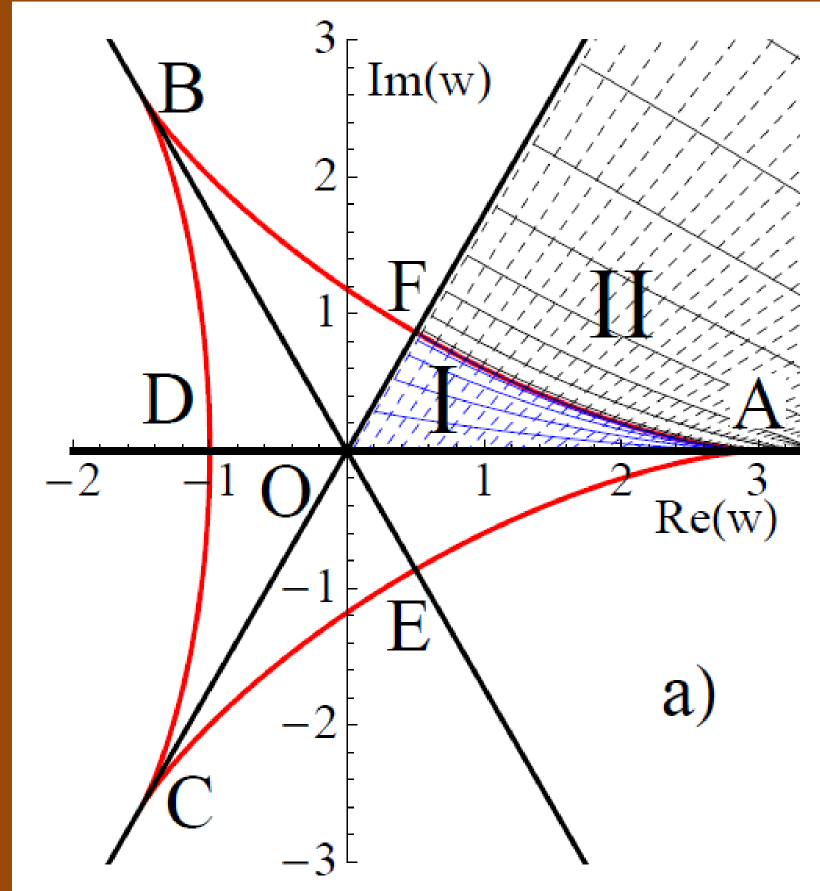
$$w = e^{-i4\alpha} + 2\cos(2\beta)\, e^{i2\alpha}$$
$$\alpha \in [0, \pi/3]$$

$$0 < \beta < \min\{3\alpha, \pi - 3\alpha\}]$$

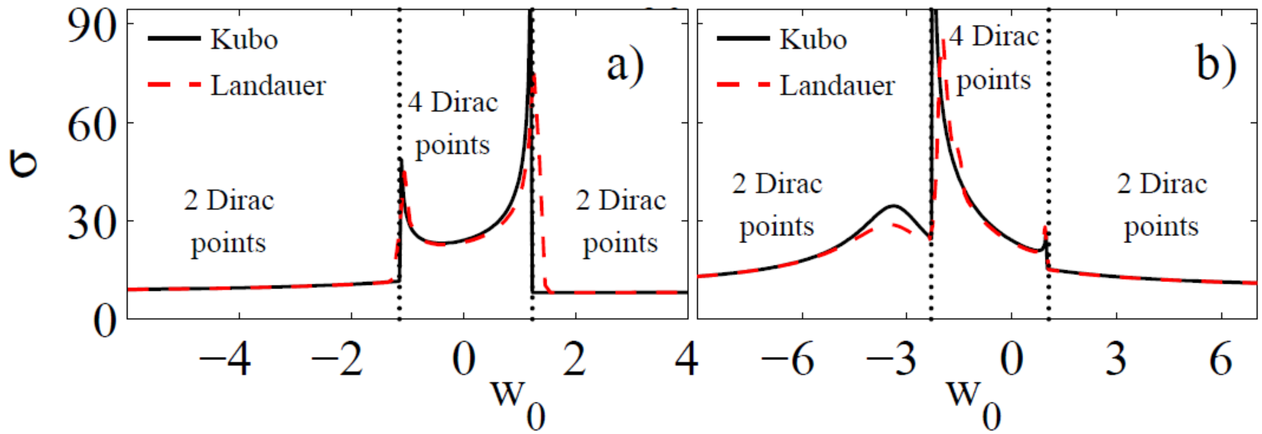
$$\frac{\boldsymbol{\sigma}_I^{min}}{8\,\sigma_0} = I_2 + \frac{1}{2\sin\beta\,(\sin 3\,\alpha - \sin\beta)} \times \begin{pmatrix} \cos^2\alpha - \sin\beta\sin\alpha & \cos\alpha(\sin\beta - \cos\alpha) \\ \cos\alpha(\sin\beta - \cos\alpha) & \sin\alpha(\sin\beta + \sin\alpha) \end{pmatrix}$$

$$i\beta < 0$$

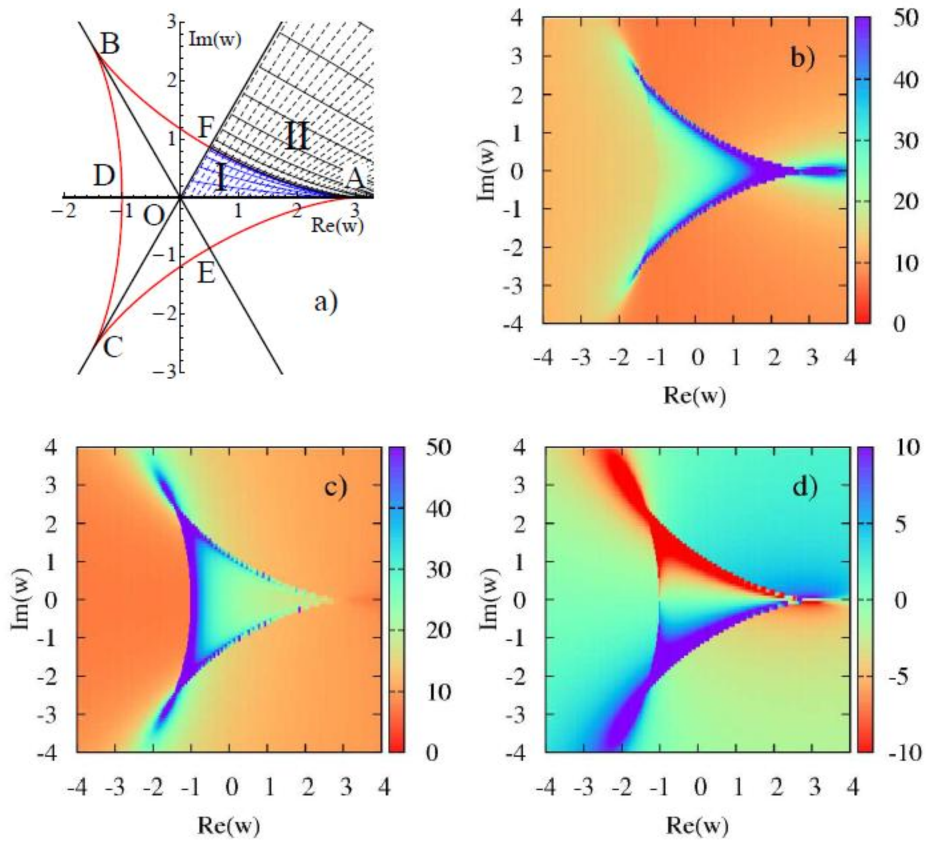
$$\frac{\boldsymbol{\sigma}_{II}^{min}}{8\,\sigma_0} = I_2 + \frac{1}{\cos^2\beta - \cos^2 3\,\alpha} \times \begin{pmatrix} \cos^2 2\,\alpha & \sin 2\alpha\cos 2\alpha \\ \sin 2\alpha\cos 2\alpha & \sin^2 2\,\alpha \end{pmatrix}$$



$$\sigma_0 = e^2/(\pi h)$$

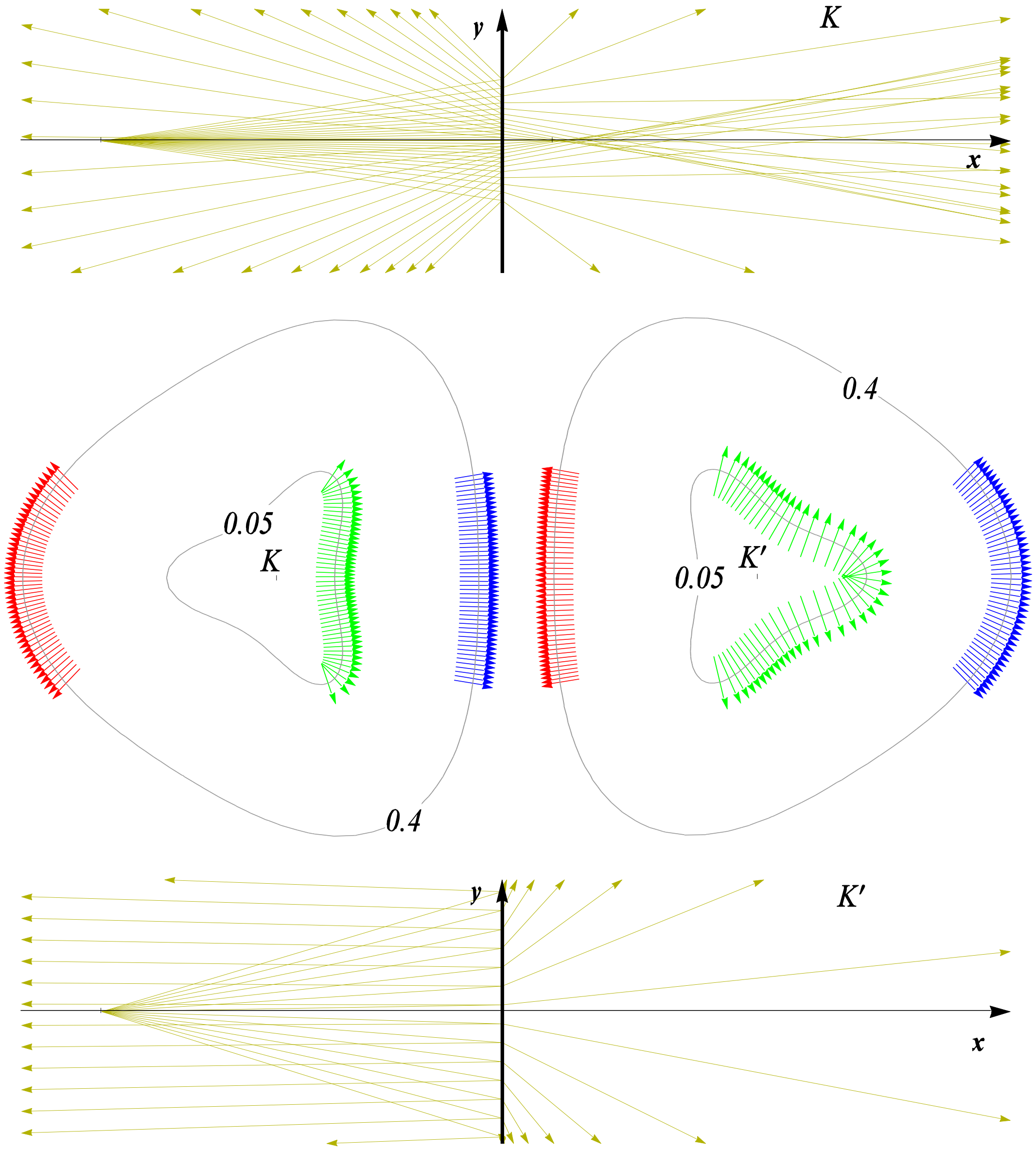


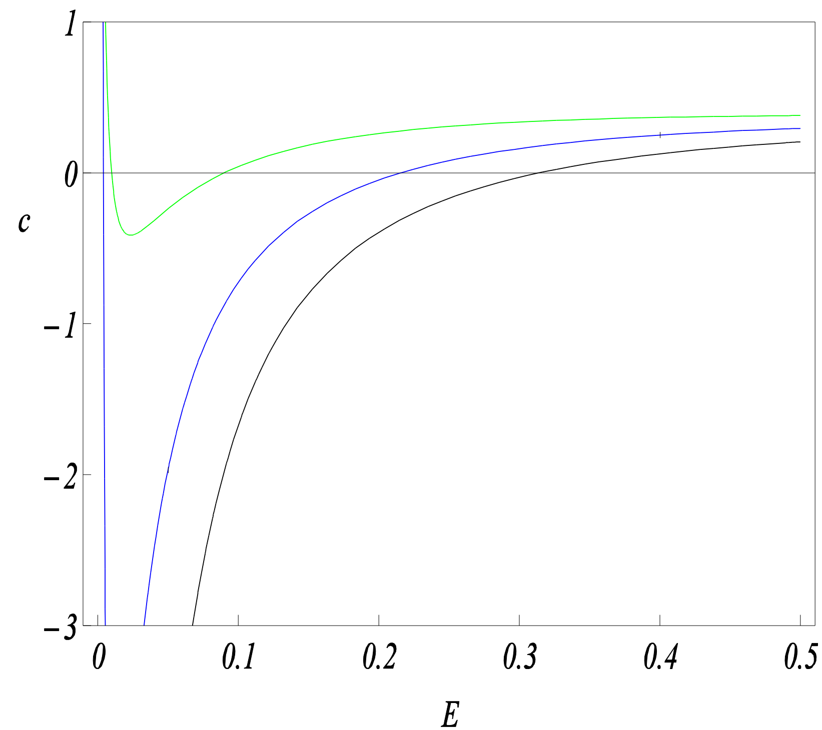
Kubo
Landauer
a)
b)
σ
4 Dirac points
2 Dirac points
2 Dirac points
4 Dirac points
2 Dirac points
2 Dirac points
w_0
w_0



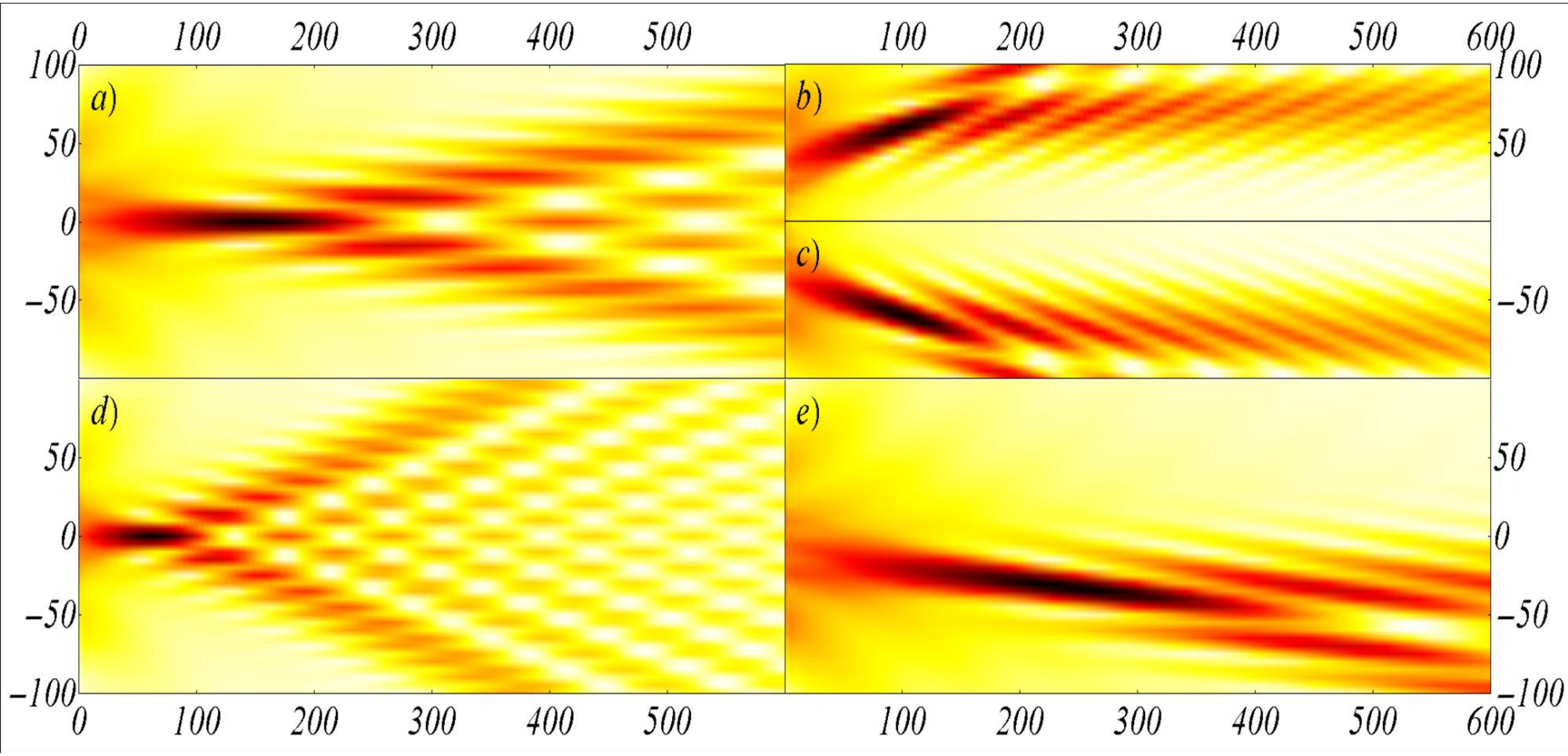
Im(w)
Re(w)
B
C
D
O
E
F
A
I
II
a)
b)
c)
d)
Im(w)
Re(w)

Elektron optika és fókuszálás egy potenciál gáton





Helyes orientáció kell!



a)
b)
c)
d)
e)
0
100
200
300
400
500
600
50
-50
-100