Multiband effects in the BEC-BCS crossover of double bilayer graphene

Sara Conti[1,2], **D. Neilson**[1], **A. Perali**[1], **M. Zarenia**[2] **and F. Peeters**[2]

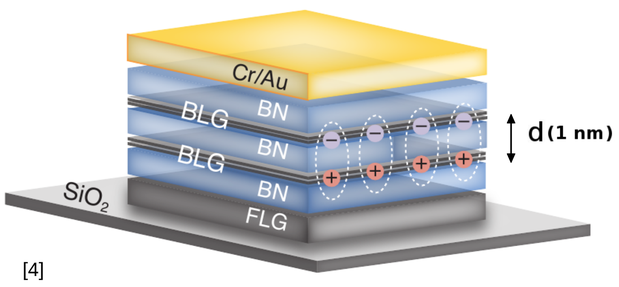
[1]Università di Camerino, 62032 Camerino (MC), Italy.

[2]Universiteit Antwerpen, CMT, 2020 Antwerpen, Belgium.

Abstract

We investigate the effect of the two energy bands, the conduction band and valence band, in bilayer graphene on the properties of BEC-BCS crossover in electron-hole double bilayer graphene[2]. We characterize the crossover by the momentum dependent superfluid gap, the condensate fraction and the evolution of the chemical potential as functions of the density and of the energy band gap between the conduction and valence bands.

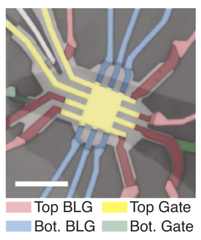
Introduction

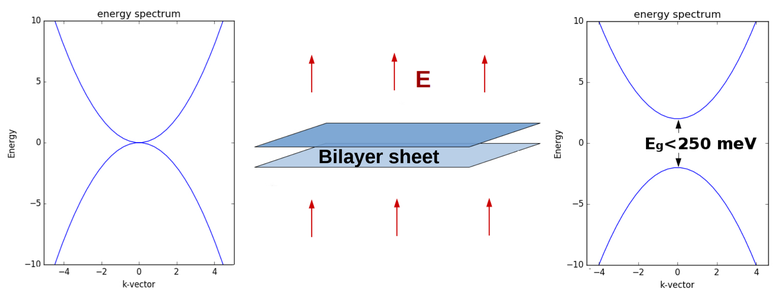


[4]

- Two graphene bilayers separated by a hBN insulating layer.
- There are electrons in one bilayer and holes in the other one.
- An electric field applied perpendicular to the bilayer sheets opens up a tunable energy gap between the bands in each bilayer.

[5]

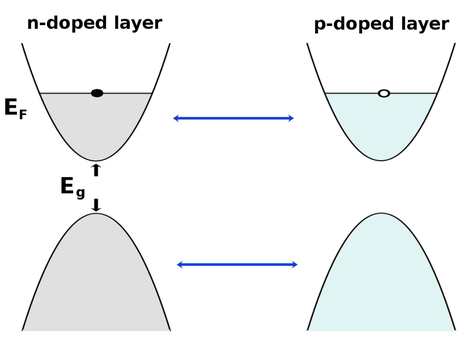




Theory

$$\xi_k^+ = \frac{\hbar^2 k^2}{2m^*} - \mu \qquad \gamma = + \text{ Conduction band}$$

$$\xi_k^- = -\frac{\hbar^2 k^2}{2m^*} - E_g - \mu \qquad \gamma = - \text{ Valence band}$$



We use multiband Mean-field theory with **intra-band pairing**.

$$H = \sum_{k\gamma} \left\{ \xi_k^{(e)\gamma}\, c_k^{\gamma\dagger}\, c_k^{\gamma} + \xi_k^{(h)\gamma}\, d_k^{\gamma\dagger}\, d_k^{\gamma} \right\} + \sum_{k,k',q,\gamma,\gamma'} V_{k\,k'}\, c_{k+q/2}^{\gamma\dagger}\, d_{-k+q/2}^{\gamma\dagger}\, c_{k'+q/2}^{\gamma'}\, d_{-k'+q/2}^{\gamma'}$$

We solve the two coupled **Gap equations**.

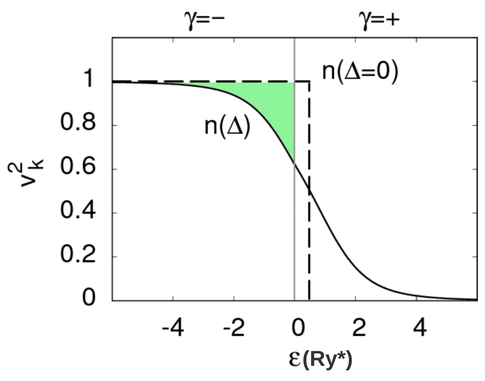
$$\Delta_k^{\gamma} = -\sum_{k',\gamma'} F_{kk'}^{\gamma\gamma'}\, V_{k\,k'}\, \frac{\Delta_{k'}^{\gamma'}}{2E_{k'}^{\gamma'}} \qquad E_k^{\gamma} = \sqrt{(\xi_k^{\gamma})^2 + (\Delta_k^{\gamma})^2} \qquad \xi_k^{\gamma} = \frac{1}{2}\left(\xi_k^{(e)\gamma} + \xi_k^{(h)\gamma}\right)$$

Form Factor $F_{\mathbf{kk'}}^{\gamma\gamma'} = \frac{1}{2}[1+\gamma\gamma'(\cos(\alpha_k)\cos(\alpha_{k'})+\sin(\alpha_k)\sin(\alpha_{k'})\cos(2\widehat{\mathbf{kk'}}))]$ $\alpha_k = \tan^{-1}\left(\frac{\hbar^2 k^2}{m^* E_g}\right)$

Coulomb Potential $V_{k\,k'} = -\frac{2\pi e^2}{\epsilon}\frac{e^{-d|\mathbf{k}-\mathbf{k}'|}}{|\mathbf{k}-\mathbf{k}'|}$

Density equation

$$n = g_s g_v \sum_{k,\gamma} (v_k^{\gamma})^2 = g_s g_v \sum_{k,\gamma} \frac{1}{2}\left(1 - \frac{\xi_{k,\gamma}}{E_{k,\gamma}}\right)$$

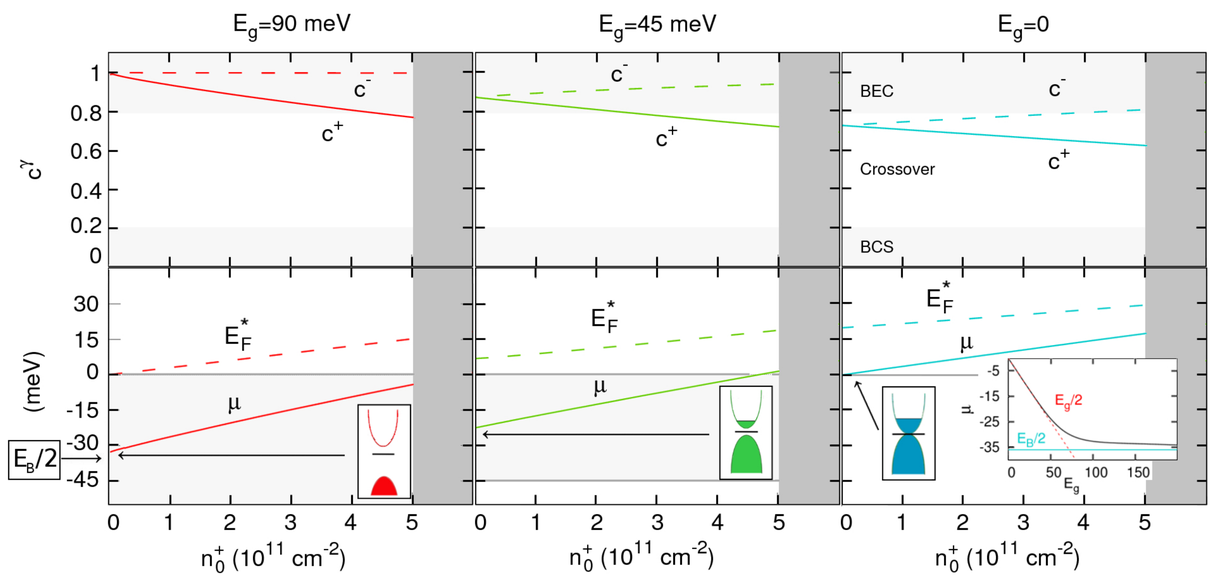


Our density control parameter is:

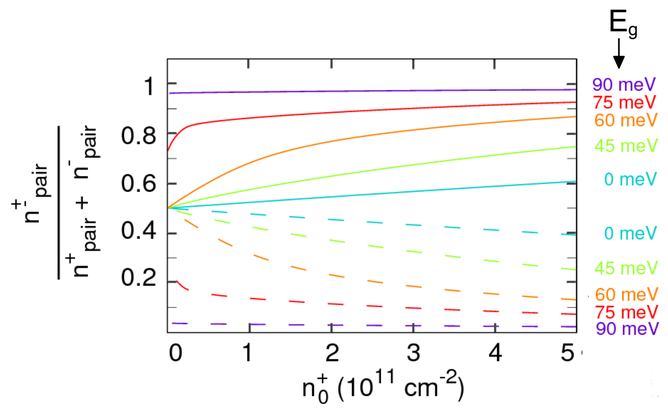
$$n_0^+ = g_s g_v \sum_k \left[(v_k^+)^2 - (u_k^-)^2\right]$$

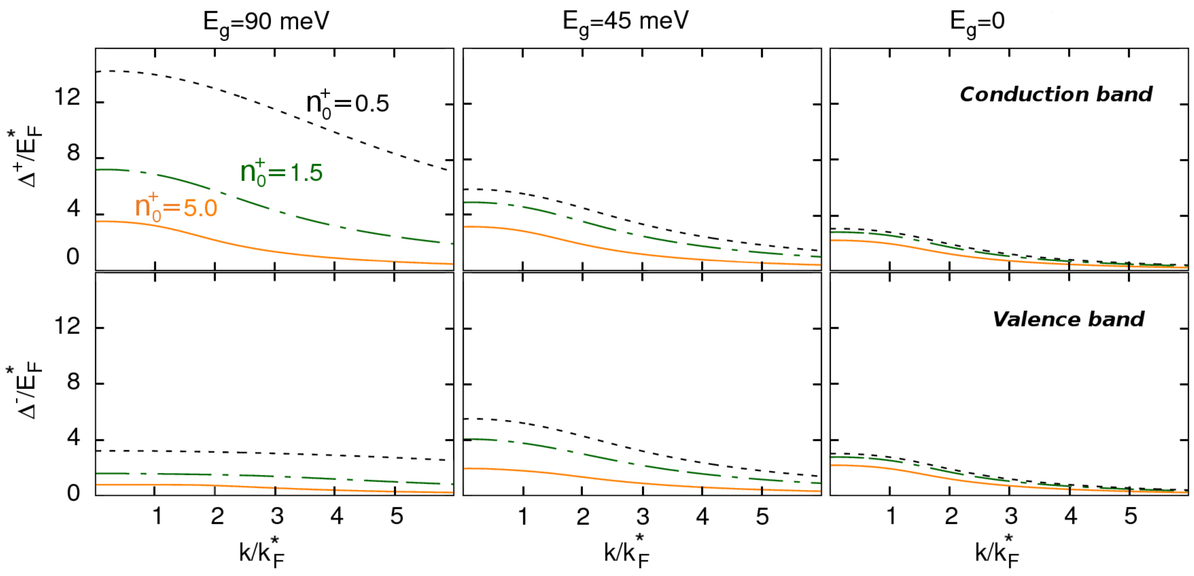
Results

Condensate fractions $c^+ = \frac{\sum_k (u_k^+)^2\,(v_k^+)^2}{\sum_k (v_k^+)^2}$, $c^- = \frac{\sum_k (u_k^-)^2\,(v_k^-)^2}{\sum_k (u_k^-)^2}$



- For **large energy band gap** E_g, the conduction band evolves as a function of increasing carrier density, from the BEC regime to the crossover regime. It cannot reach the BCS regime because of the strong screening at high density that kills the superfluidity.
- For **small energy band gap** E_g, the proximity of the two bands prevents the system from entering the BEC regime at low carrier densities.
- The valence band remains in the BEC regime for all carrier densities.
- Multiband effects are important in the **low density region**.
- There are two different limiting behaviours of chemical potential at low density, depending on E_g.





- For **large energy band gap**, the system is well approximated by a one band system. The superfluid gap equations become decoupled and pair formation is confined to the conduction band. The system evolves following the conduction band.
- For **small energy band gap**, the system does not evolve. The superfluid gap equation are coupled and both the bands equally contribute to the pair formation.

References

1) A.Perali, D.Neilson, and A.R.Hamilton, *High-temperature Superfluidity in double-bilayer graphene*, Phys. Rev. Lett. 110, 146803 (2013).

2) M.Zarenia, A.Perali, D.Neilson and F.M.Peeters, *Enhancement of electron-hole superfluidity in double few-layer graphene*, Scientific Reports 4,7319 (2014).

3) J.I.A.Li, T.Taniguchi, K.Watanabe, J.Hone, A.Levchenko, and C.R.Dean, *Negative Coulomb Drag in Double Bilayer Graphene*, Phys. Rev. Lett. 117, 046802 (2016).

4) K.Lee, J.Xue, D.C.Dillen, K.Watanabe, T.Taniguchi, and E.Tutuc, *Giant Frictional Drag in Double Bilayer Graphene Heterostructures*, Phys. Rev. Lett. 117, 046803 (2016).

5) J.I.A.Li, T.Taniguchi, K.Watanabe, J.Hone, C.R.Dean, *Excitonic superfluid phase in Double Bilayer Graphene*, arXiv:1608.05846 [cond-mat.mes-hall] (2016)

Sara Conti **sara.conti@uantwerpen.be, sara.conti@unicam.it**