

# Reduction of the Normal-Superfluid Transition Temperature in Gated Bilayer Graphene

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## INTRODUCTION

We show that the normal-superfluid transition in bilayer graphene (BLG) predicted to occur at high temperature is strongly affected not only by the dielectric constants of the insulators, but also by the proximity of ideal metal gates. Even assuming optimistically an unscreened interlayer Coulomb interaction, we find that for a gate-insulator thickness smaller than 2-to-5 nm of equivalent SiO<sub>2</sub> thickness ( $t_{eq}$ ), the transition temperature is depressed to the 1 K-1 mK range. Thus, thicker and low- $\kappa$  gate insulators are required to design transistors exploiting the properties of the superfluid state. We also use density functional theory (DFT) to estimate the strength of the Coulomb interaction in BLG embedded in hBN and interlayer tunneling for tunnel-FET applications.

## SUPERFLUIDITY IN GBLs and BiSFETs

A transition from a normal to a superfluid state has been predicted to occur in BLG at temperatures approaching 300 K [1]. Biasing the BLG so that equal densities of electrons and holes are induced in the two layers, strong Coulomb interactions cause the excitonic pairing of electron and holes with opposite momenta and their Bose-Einstein condensation, as in BCS theory, the “which layer” degree of freedom (“pseudospin”) replacing spin. Based on these predictions, novel low-power high-performance devices exploiting the unique properties of the condensate have been proposed (bilayer pseudospin field-effect transistors, BiSFETs) [2].

The expression for the superfluid gap at the Fermi surface,  $\Delta(k_F)$ , is given by the integral equation:

$$\Delta(k) = \int \frac{d\mathbf{k}'}{(2\pi)^2} eV(\mathbf{k} - \mathbf{k}') \frac{1 + \cos \phi}{2} \frac{\Delta(\mathbf{k}')}{2E(\mathbf{k}')}$$

where  $k_F$  is the Fermi wavevector,  $V(q)$  is the interlayer Coulomb interaction, and  $E(k)^2 = \Delta(k)^2 + \hbar^2 v_F^2 (k - k_F)^2$  ( $v_F$  being the Fermi velocity). As discussed in Ref. [3], there are diverging opinions on how to account correctly for the dielectric screening of  $V(q)$ . The values for the gap calculated in terms of the Fermi energy  $E_F$  range from  $\Delta(k_F) \sim 0.1 E_F$  (unscreened interaction as in [1], corresponding to a transition temperature  $T_C \sim 100$  K) to  $\Delta(k_F) \sim 10^{-7} E_F$  (statically

screened as in [4],  $T_C \sim 1$  mK), a huge difference with obvious practical implications. In all cases, only the ideal geometry of BLGs embedded in an infinite dielectric medium has been considered. In practice, however, in trying to detect the phase transition and in designing BiSFETs, one must employ a gated and supported BLG. Here we show that even assuming the very optimistic scenario of an unscreened interlayer interaction, the proximity of ideal metal gates screens the interaction to the extent of reducing  $T_C$  to values too small to be of practical use or even observable.

## SIMULATION METHODS AND RESULTS

We have considered BLGs with interlayer separation  $d \sim 1$  nm and either a single metallic gate at a distance  $t$  above the top layer or a symmetric double-gate geometry. We indicate with  $\kappa_s$ ,  $\kappa_i$ , and  $\kappa_g$  the dielectric constants of the substrate/bottom dielectric, interlayer and gate dielectrics, respectively. We have obtained the Green’s function for the Poisson equation in the BLG geometry, derived the expression for the interaction potential  $V(q)$ , and solved iteratively the gap integral equation to calculate the gap  $\Delta(k)$ .

To summarize our main results: For single-gate geometries a very close gate ( $t_{eq} = 1$  nm) reduces the magnitude of the gap to insignificant levels and even more so in the presence of a strong dielectric mismatch (Fig. 1). Figure 2 quantifies this conclusion showing that, even in homogeneous low- $\kappa$  environments,  $t_{eq}$  as large as 5-to-10 nm are required to maintain a high  $T_C$ . The effect of a dielectric mismatch is emphasized in Fig. 3, while Fig. 4 shows how a double gate affects negatively the already pessimistic conclusions of Fig. 2: Only thick ( $t_{eq} > 10$  nm), low- $\kappa$  ( $< 2$ ) gate insulators can afford the observation of the phase transition, but with this constrain the design of BiSFETs faces significantly challenges. These results are based on the idealized case of ‘delta-function’ charges localized on the graphene sheet, so DFT calculations are used to estimate  $V(q)$ , as well as interlayer tunneling, in a ‘real’ BLG-hBN system accounting for the spatial extent of the electronic (pseudo)wavefunctions.

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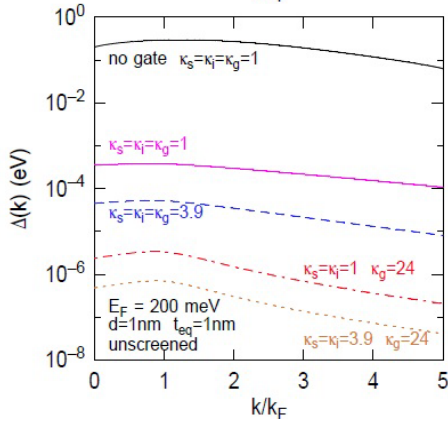


Fig. 1. Calculated superfluid gap as a function of wave vector assuming an unscreened interlayer interaction, the dielectric geometries shown in the legend and  $t_{eq}=1$  nm.

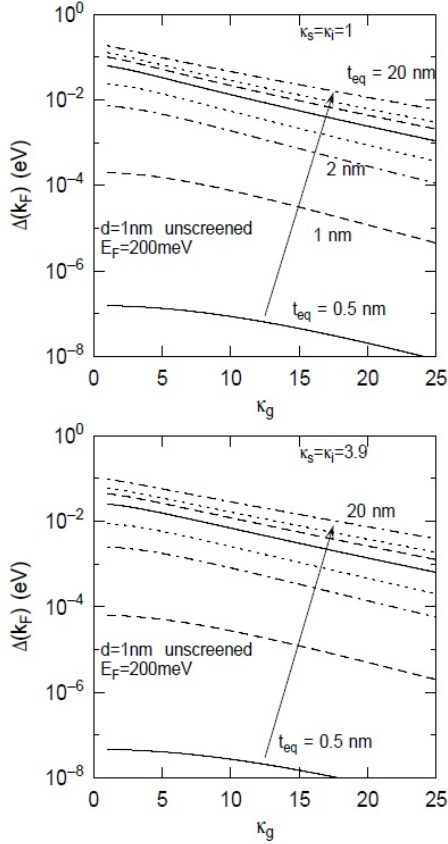


Fig.2. Dependence of the calculated gap at the Fermi surface on the dielectric constant  $\kappa_g$  of the gate insulators assuming  $\kappa_s = \kappa_i = 1$  (top) or 3.9 (bottom). The curves are parametrized by the value of the equivalent oxide thickness of the gate insulator,  $t_{eq} = 0.5, 1, 2, 3, 5, 7.5, 10,$  and  $20$  nm.

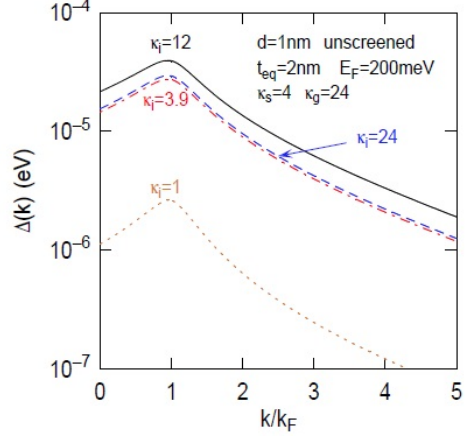


Fig. 3. Calculated gap  $\Delta$  for a single-gate geometry as a function of wave vector  $k$  assuming an unscreened interaction, and the parameters shown. The four curves are labeled by the relative dielectric constants of the interlayer dielectric,  $\kappa_i = 1$  (dotted line), 3.9 (dash-dotted line), 15 (solid line), and 24 (dashed line). Note that in the presence of a high- $\kappa$  gate insulator a low- $\kappa$  interlayer dielectric may actually be counterproductive. An optimum  $\kappa_i$  is seen at  $\approx 12$  since a larger value suppresses the direct attractive interlayer interaction whereas a lower value induces a large interface polarization charge that screens the interaction.

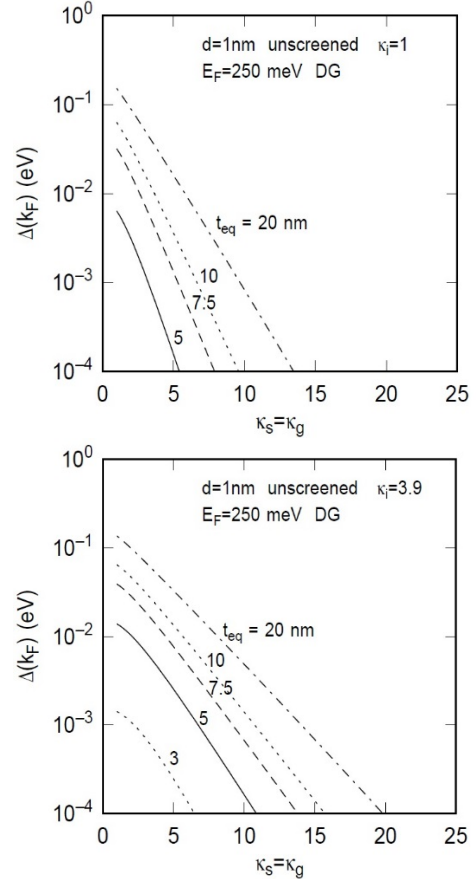


Fig. 4. As in Fig. 2 but for a symmetric double-gate geometry. Note how the presence of a bottom gate depresses the superfluid gap even more for large dielectric constants of the two gate insulators (here assumed to be equal).