Metastable Dynamics of Graphene Excitonic Condensates

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INTRODUCTION

Excitonic superfluids of indirectly bound excitons have been intensively studied as a posible mechanism for realizing ultra-efficient information processing devices[1]. Much of non-equilibrium response of the system below critical current (I_c), the máximum intersurface current that preserves the condensate, is well understood[2]. However, the behavior past I_c has not been studied. The lack of information in this regime is due to the absence of a time independent solution beyond I_c[3]. This evidence supports the establishment of quasistable time-dependent dynamics after I_c. In this work, we study the time-dependent dynamics of this system, we study spatially segregated, strongly interacting monolayers using a time-dependent nonequilibrium green function (NEGF) method[4]. We find that a non-zero electric field in the presence of a suppressed condensate generates the acceleration of the remaining superfluid component with a corresponding 2π winding of the order parameter phase[5]. Furthermore, we find that currents well past I_c form stable oscillating states with frequencies in the THz regime. These states are tunable based on the bias across the layer. Our results not only shed light on a previously unexplored regime of condensate dynamics but also have significant implications for high-frequency oscillators.

MODEL

We use time dependent nonequilibrium green function method[4] to understand dynamics of bilayer excitonic condensate after I_C. In general, the bilayer with coloumb interaction is considered with hamiltonian[3]

$$H = \begin{bmatrix} H_{top} & \Delta_{\mathrm{sas}} - \mathrm{U}\langle \mathrm{m_x} - i\mathrm{m_y}\rangle \\ \Delta_{\mathrm{sas}} - \mathrm{U}\langle \mathrm{m_x} + i\mathrm{m_y}\rangle & H_{bot} \end{bmatrix} \quad (1)$$

$H_{top} = H_{bot} = -t\sum_{\langle r_1, r_2\rangle} c^{\dagger}{}_{r1} c_{r2}$ is non-interacting hamiltonian of the layer with t=-3eV. Δ_{sas} is the single particle tunneling amplitude of bilayer. $U(=e^2/\varepsilon d)$ is the onsite coloumb interaction parameter, here we consider interlayer spacind d=1nm. m is the pseudospin orientation given by $\vec{m} = Re(\rho_{\uparrow\downarrow})\,\hat{x} + Im(\rho_{\uparrow\downarrow})\,\hat{y} + (\rho_{\uparrow\uparrow} - \rho_{\downarrow\downarrow})\hat{z}$. ρ is the density matrix and the psuedospin index represents the layer degree of freedom. The time step is achieved by propagating self consistently prepared initial green function coupled with poisson solver. While proper time step must be small enough to energy scale($E\Delta t<1$) and large enough to capture the relevant dynamics, we use $\Delta t=0.03(a.u.)$. We use counter flow geometry ($V_{topright}=-V_{topleft}=V_{interlayer}$) to maximze the excitonic supercurrent. In Fig.1, we illustrate the device geometry that we consider in this work.

RESULTS

We find that evolution of supercurrent past I_c due to excessive bias eventually leads to a broken condensate phase characterized by the coexistence of both a superfluid component and a normal component. Since the condensate state becomes energetically unstable, the superfluid density will decay into single particle tunneling scale and its phase rotation persists. However, we find that for small interlayer bias past critical current(~0.1V) the superfluid density shows quasistable oscillation(~100THz). The frequency of the oscillation rapidly increases with $V_{interlayer}$. In Fig.2, we present the simple calculation of 1D semiconductor bilayer with particle-hole symmetry. We observe both nonzero net interlayer current and stable coherent counter flow in bottom layer. This indicates that stable oscillation between normal and superfluid components. In Fig. 3, we see rather than decaying of superfluid density, the system launches normal fluid followed by 2π phase slip as shown. This phase slip relaxes the

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supercurrent and the oscillation between superfluid and normal fluid occurs.

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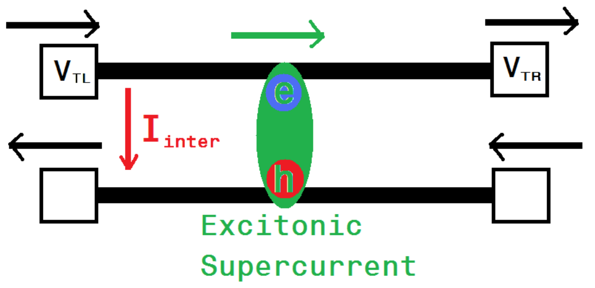

Fig1. Schematic illustration of the bilayer system. In counter drag flow geometry, Bias is only applied in top layer. Enhanced tunneling lead to the current of opposite direction to flow in another layer. To conserve momentum and charge, the system launches excitonic supercurrent. In metastable regime, the system periodically launches normal fluid due to the oscillatory destruction of superfluidity

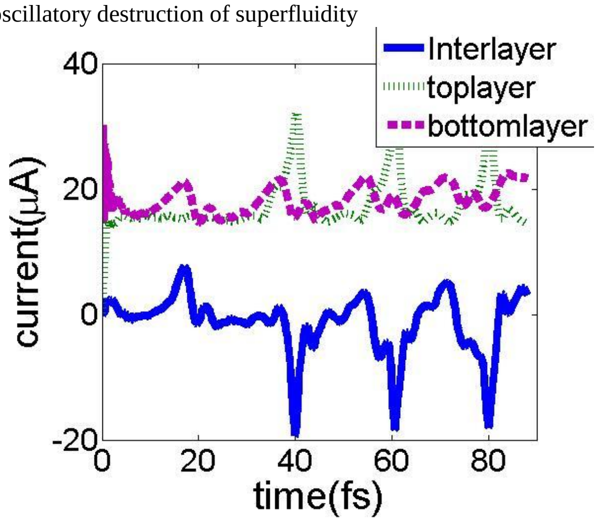

Fig 2. Current vs. time profile just past I_C. Oscillatory current is observed. Nonzero net interlayer current is the consequence of the broken coherence of the bilayer.

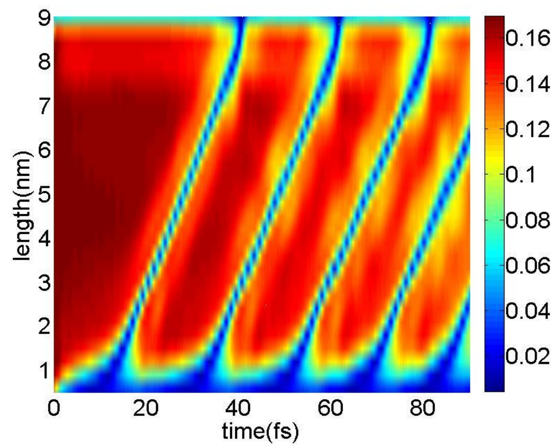

Fig 3. Magnitude of exciton condénsate order parameter. While magnitude of order parameter can be considered as superfluid density, Propagating blue line indicates that the system lauches normal fluid wave packet to relax excessive winding of order parameter phase. After blue line pass through the región, the order parameter recovers its original superfluid density.

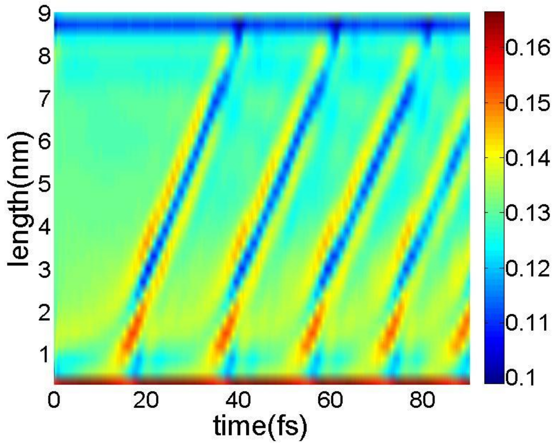

Fig 4. Desnity fluctuation (occupation number) in bottom layer. Comparing with Fig 3. We see that density fluctuation line corresponds to the normal fluid propagation. This means that net interlayer current is accompanied with normal fluid line. When exciton pair is broken, the psuedospin orientation becomes unstable. Eventually it leads to the nonzero net current hopping top and bottom layer back and forth.