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Electrical Reservoirs for Bilayer Excitons

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The ground state of two-dimensional (2D) electron systems with equal low densities of electrons and holes in nearby layers is an exciton fluid. We show that a reservoir for excitons can be established by contacting the two layers separately and maintaining the chemical potential difference at a value less than the spatially indirect band gap, thereby avoiding the presence of free carriers in either layer. Equilibration between the exciton fluid and the contacts proceeds via a process involving virtual intermediate states in which an unpaired electron or hole virtually occupies a free carrier state in one of the 2D layers. We derive an approximate relationship between the exciton-contact equilibration rate and the electrical conductances between the contacts and individual 2D layers when the contact chemical potentials align with the free-carrier bands, and explain how electrical measurements can be used to measure thermodynamic properties of the exciton fluids.

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Introduction.—Excitons are composite bosonic particles in which conduction band electrons bind with valence band holes. Excitons normally exist as excited states of semiconductors and insulators, and can have extremely long lifetimes when the electron and hole are separated in momentum-space, or in real-space [1], or both. Bose-Einstein condensation of long-lived excitons was predicted several decades ago [2], and is thought to have been realized relatively recently in semiconductor quantum well [3] double-layers. Closely related polaron condensate states, in which longer range coherence is assisted by the small masses of 2D vertical cavity photons, are regularly realized and have been studied extensively over the past decade [8–18]. In typical exciton-condensation experiments a population of electrons and holes is generated in nearby 2D layers by optical excitation. Free electrons and holes can also be injected electrically if contacts can be established to conduction and valence bands. [19–23]. The electrons and holes then combine to form excitons and the excitonic state is revealed by photons emitted during the exciton radiative decay process [23–25]. In this paper we propose and theoretically analyze a mechanism that allows direct electrical control of the chemical potential of spatially indirect exciton condensate states, in which longer range coherence is assisted by the small masses of 2D vertical cavity photons, and holes in nearby layers is an exciton fluid. We show that a reservoir for excitons can be established by contacting the two layers separately and maintaining the chemical potential difference at a value less than the spatially indirect band gap, thereby avoiding the presence of free carriers in either layer. Equilibration between the exciton fluid and the contacts proceeds via a process involving virtual intermediate states in which an unpaired electron or hole virtually occupies a free carrier state in one of the 2D layers. We derive an approximate relationship between the exciton-contact equilibration rate and the electrical conductances between the contacts and individual 2D layers when the contact chemical potentials align with the free-carrier bands, and explain how electrical measurements can be used to measure thermodynamic properties of the exciton fluids.

vdW heterojunctions involving 2D semiconductors can host spatially indirect excitons formed from electrons and holes in two different layers with binding energies that remain large, even when the electron and hole layers are separated by hBN layers that increase exciton lifetimes by orders of magnitude from the nanosecond range (32–34) that applies in the absence of spacer layers.

When the chemical potentials of contact electrodes are inside the energy gaps of the 2D semiconductors, electrons cannot tunnel into double-layer band states. However, because of the Coulomb interaction and the exciton binding energy that it produces, correlated pair tunneling from electrodes connected to the two different layers is possible. In this Letter, we develop a microscopic model of this two-particle tunneling process and argue that it can allow electrode pairs to act directly as exciton reservoirs with a well-defined chemical potential set by the source-to-drain bias. Direct exciton reservoirs have advantages for exciton generation and control over the commonly employed indirect optical and electrical generation processes that start by generating free electrons and holes, and we expect in particular that they will enable electrical measurements of the transport properties of exciton fluids.

Correlated pair tunneling.—We consider the vertically stacked multilayer heterostructure system illustrated in

FIG. 1. (Color online) Schematic illustration of a 2D material heterojunction capable of supporting a spatially indirect exciton condensate, and of an electrode pair that can act as a reservoir for spatially indirect excitons.
The total Hamiltonian of the four-layer system is

$$\hat{H} = \hat{H}_S + \hat{H}_D + \hat{H}_{DL} + \hat{H}_t,$$

where $\hat{H}_S$ and $\hat{H}_D$ are the linear band Hamiltonians of the graphene electrodes, and $\hat{H}_{DL}$ is the DL Hamiltonian including Coulomb interactions. In this paper we assume that the TMD DL is in its exciton condensate ground state and ignores its spin degree of freedom. Tunneling between the electrodes and the double-layer system is accounted for by

$$\hat{H}_t = \sum_{k,p} t_{kp}^{S} \hat{c}_{k,T}^\dagger \hat{a}_{p,S} + t_{kp}^{D} \hat{c}_{k,T}^\dagger \hat{a}_{p,D} + h.c.$$

where $t_{kp}^{S(D)}$ is a tunneling matrix element. $\vec{p} \equiv (p, \lambda, \tau)$ is a compound index that combines the 2D momentum $p$, the band index $\lambda = c, v$ and the valley index $\tau$ of the graphene electrode states. In Eq. (2), $\hat{a}$ is the creation operator in the electrodes and $\hat{c}_{T(B)}^\dagger$ is the creation operator for conduction band electrons in T and valence band electrons in B. For single-grain hBN tunnel barriers, the tunneling properties can have very specific momentum dependence which does not play an essential role and is not accounted for below, but is sensitive to the relative orientation of the various 2D material layers. We neglect interlayer tunneling between the T and B primarily because we are interested in a bias voltage regime in which free carriers are not present to tunnel. We also set the interlayer radiative recombination rate to zero in order to focus on double-electrode reservoir properties.

In practice we anticipate that the interplay between our exciton reservoirs and interlayer radiative recombination, whose strength can be adjusted over orders of magnitude by varying the thickness and orientation of the hBN barrier layer, opens up a rich range of opto-electronic phenomena for study that are a primary motivation for this work.

The band diagram of the vertical vdW heterostructure system is shown schematically in Fig. 2. At zero bias (Fig. 2(a)), we assume that both graphene electrodes are neutral and that the aligned Dirac points are in the middle of the spatially indirect band gap $E_g$. When a bias voltage in the subgap regime ($E_g > eV_b > 0$) is applied, tunneling between the electrodes and free-carrier states in the TMD layers is prohibited by energy conservation. (Note that $E_g$ increases with $V_b$, and that direct tunneling of electrons from source to drain is extremely strongly suppressed because it must navigate three tunneling barriers.) Our interest here is in the bias regime $E_g > V_b > \mu^0_{ex}$, where $\mu^0_{ex}$ is the energy of an isolated spatially indirect exciton. In this bias voltage regime energy conservation can be achieved by the two-particle tunneling process illustrated in Fig. 2(b). The state created when an electron from S tunnels to a virtual state in T and a hole from D subsequently tunnels to B has a finite overlap with an exciton fluid state (path 1). An alternative and equally possible path is for a hole from D to tunnel to a virtual state in B first (path 2). Each tunneling process effectively transfers one electron from S to D and creates an exciton in the DL. We concentrate here on the case of $T < T_c$ for which the excitons form a condensate, although the main idea of using an electrode pair as a reservoir for excitons applies equally well when the excitons form a non-condensed gas. For the low temperature case, we find that because of the stimulated scattering characteristic of bosonic statistics, a major fraction of the excitons added or removed from the system are simply added or removed from the condensate.
BCS-like mean field theory approach in which the ground state is found by minimizing $\langle \hat{H}_{DL} - \mu_{ex} N \rangle$ in the space of Slater determinant states with coherence between conduction and valence bands. Here $N = \sum_k \langle \hat{c}_{k,T} \hat{c}_{k,T}^\dagger \rangle / 2$ is the total number of electron-hole pairs. The mean-field Hamiltonian of the exciton condensate system is

$$\hat{H}_{MF}^{DL} = E_G + \sum_k E_k (\hat{\gamma}_{k,0}^\dagger \hat{\gamma}_{k,0} - \hat{\gamma}_{k,1}^\dagger \hat{\gamma}_{k,1}) + \mu_{ex} N$$  \hspace{1cm} (3)

where $E_G$ is the condensate ground state energy and $\mu_{ex}$ the exciton chemical potential. The quasiparticle energy dispersion is $E_k = \sqrt{(\epsilon_k^T - \mu_{ex}/2)^2 + \Delta_k^2}$, where we have assumed that the DL energy dispersion $\epsilon_k^T = -\epsilon_k^B = h^2 k^2 / (2m)$ and that the order parameter $\Delta_k$ is real. $\hat{\gamma}_{k,0}^\dagger = u_k \hat{c}_{k,T}^\dagger + v_k \hat{c}_{k,B}^\dagger$ and $\hat{\gamma}_{k,1}^\dagger = v_k \hat{c}_{k,T}^\dagger - u_k \hat{c}_{k,B}^\dagger$ are creation operators for states in the empty and occupied quasiparticle bands, respectively, and $u_k$ and $v_k$ are coherence factors that depend on the pair potential $\Delta_k$ which is determined in turn by solving a self-consistent equation that has solutions only if $\mu_{ex}$ exceeds $\mu_{ex}^0$ [39].

The two-particle tunneling rate can be obtained by applying Fermi’s golden rule to the second order tunneling process. We find that the net rate at which excitons are added to the condensate is

$$\frac{dn_{ex}}{dt} = \frac{2\pi}{\hbar A} \sum_{\mathbf{p},\mathbf{p}' \neq \mathbf{p}} |M_{\mathbf{p}\mathbf{p}'}|^2 (f_{\mathbf{p}}^S - f_{\mathbf{p}}^D) \delta(\epsilon_{\mathbf{p}} - \epsilon_{\mathbf{p}'} - \mu_{ex})$$  \hspace{1cm} (4)

where $f_{\mathbf{p}}^\alpha$, with $\alpha = S, D$, is the Fermi distribution function. The matrix element in Eq. (4)

$$M_{\mathbf{p}\mathbf{p}'} = \sum_k u_k v_k a_{\mathbf{p}k}^S a_{\mathbf{p}'k}^D \left( \frac{1}{E_0^0 - \epsilon_{\mathbf{p}}^S - \epsilon_{\mathbf{p}'}^D - \mu_{ex}} \right)$$  \hspace{1cm} (5)

where $E_0^0 = E_k + \mu_{ex}/2$ and $E_0^1 = -E_0^0$ are the energies required to add quasiparticles of momentum $\mathbf{k}$ to bands 0 and 1, respectively. The energy denominators account for the finite energy cost of hopping to the intermediate virtual states, and never vanish in the bias voltage range of interest. The two terms in the matrix element account for the two tunneling paths depicted in Fig. 2b.

The evaluation of $|M_{\mathbf{p}\mathbf{p}'}|^2$ in Eq. (5) requires knowledge of the momentum dependent tunneling amplitudes $\mu_{\mathbf{k}\mathbf{p}}^\alpha$. We simplify our calculation by assuming that interfacial disorder plays an important role in determining the tunneling amplitude. We employ a Gaussian random tunneling model for which $\langle \mu_{\mathbf{k}\mathbf{p}}^\alpha \mu_{\mathbf{k}\mathbf{p}'}^\beta \rangle_{\text{dis}} = 0$ and the second order correlation functions satisfy

$$\langle \mu_{\mathbf{k}\mathbf{p}}^\alpha(r) \mu_{\mathbf{k}\mathbf{p}'}^\beta(r') \rangle_{\text{dis}} = |\Delta t|^2 \mathcal{F}(r - r') \delta_{\alpha\beta},$$  \hspace{1cm} (6)

where $\langle \cdots \rangle_{\text{dis}}$ is the disorder average and $\mathcal{F}(r - r')$ is a smoothly decaying function of the distance $|r - r'|$. For low exciton densities and $V_b > \mu_{ex}^0$ limit, we obtain the tunneling current-voltage equation

$$I_{ex} \approx G_{ex} (V_b - \mu_{ex}/e).$$  \hspace{1cm} (7)

$G_{ex}$ is the exciton tunneling conductance $G_{ex}$ is given approximately by

$$G_{ex} = \frac{A g_N^S g_N^D n_{ex} a_B^2}{e^2 / \hbar} \frac{8}{\rho_0 E_b},$$  \hspace{1cm} (8)

where $g_N$, $g_B$ are the normal tunneling conductances per unit area between $S$ and $T$ and between $D$ and $B$, respectively, $\rho_0$ is the density of states of quasiparticle band 0, $a_B$ is the Bohr radius, and $E_b$ the exciton binding energy. The tunneling conductance in Eq. (8) is proportional to the exciton condensate density $n_{ex}$ because of the bosonic stimulated scattering effect. Since the fraction of uncondensed excitons is small in the low density BEC limit, we have assumed in deriving this simple result that the contributions from processes with a final state exciton outside the condensate are negligible. Using the typical values $g_N^S = g_N^D \sim 10^{-2} e^2 / h \cdot \mu m^{-2}$, $a_B^2 \sim 0.01$, and taking the quasiparticle band masses in the TMD layers close to the bare electron mass, we estimate that $G_{ex}$ is in the order $10^{-11} e^2 / h \cdot \mu m^{-2}$.
in which the spatially indirect band gap is tuned electrically by varying \( V_b \). We do not emphasize this distinction between equilibrium and quasi-equilibrium below.

**Electrical characteristics of exciton reservoirs.**—
Because of repulsive interactions between excitons, their chemical potential increases with exciton density [39–41]. For spatially indirect excitons \( \mu_{ex} = \mu_{ex}^0 + (g_H + g_{XC})n_{ex} \), where \( g_H = e^2/C_{DL} = \epsilon/(4\pi e C_{DL}) \) and \( g_{XC} \) are the Hartree and exchange-correlation contributions to the effective exciton-exciton interaction. The Hartree term accounts for the capacitive coupling between T and B layers, whereas \( g_{XC} \), which is density-dependent and cannot be evaluated exactly, accounts for exchange and correlation effects due to both intralayer and interlayer Coulombic interactions and therefore also depend on the interlayer spacing \( d_{DL} \). When we add the potential energy associated with charged electrodes, the exciton chemical potential in our geometry has an additional electrostatic contribution:

\[
\mu_{ex} = \mu_{ex}^0 + (g_H + g_{XC})n_{ex} + g_H n_S \tag{9}
\]

where \( n_S = n_D \) are the equal densities of electrons and holes in the two electrodes. Eq. [9] can be obtained by minimizing the total energy, \( \mathcal{E}[n_S, n_{ex}] \), with respect to \( n_{ex} \) (see Supplemental Material [42]). By minimizing \( \mathcal{E}[n_S, n_{ex}] \) with respect to \( n_S \) we obtain the following expression for the bias potential:

\[
\frac{n_{ex}}{C_{DL}} + n_S \left( \frac{2h\nu/\sqrt{2\pi}}{e^2/|n_S|} + \frac{1}{C_{geo}} \right) = \frac{V_b}{e}. \tag{10}
\]

In Eq. [10], \( C_{geo} = \epsilon/(4\pi e^2 d_{tot}) \) is the geometric capacitance and \( d_{tot} = d_S + d_{DL} + d_D \); the energy function used to derive Eq. [10] does not account for exchange and correlation in the electrodes, i.e. for interaction corrections to the electrode quantum capacitance, but these can easily be added when relevant. A time-independent equilibrium between the electrodes and the exciton fluid is established when \( n_{ex} \neq 0 \) and electron-hole pairs have the same chemical potential in either environment i.e. when and \( eV_b = \mu_{ex} \).

Fig. 3 shows equilibrium densities calculated for several typical values of the dimensionless exchange-correlation coupling strength \( \beta = g_{XC}/g_H \). Below we take \( \beta \) as an unknown parameter and show that its value can be measured electrically. When estimated using self-consistent mean-field theory \( \beta \) changes sign from positive to negative when \( d_{DL} \) exceeds around a quarter of an excitonic Bohr radius, and using TMD semiconductor parameters has the value \( \beta = -0.6 \) for \( d_{DL} = 1 \text{nm} \) in [41]. Below the threshold voltage \( V_{th} \), which satisfies \( eV_{th} = \mu_{ex}^0 + g_H n_S(V_{th}) \) and depends on \( d_S/d_{DL} \), no excitons are injected and \( n_S(V_b) \) is independent of \( \beta \), as shown in Fig. 3(a). When \( V_b > V_{th} \), electrons and holes can enter the TMD layers by forming excitons via the two-particle tunneling process. The slope of the \( n_S(V_b) \) curve is reduced and becomes negative when \( \beta \) changes sign from positive to negative. For \( \beta < 0 \), we find that \( n_S \) becomes negative when \( V_b = -\mu_{ex}^0/\beta \); we show later that the dynamic response is anomalous at this point.

The two-particle tunneling rate which we have estimated theoretically can be measured by performing ac electrical measurements, letting \( V_b(t) = V_{ac} + V_{dc} \cos \omega t \), where \( V_{ac} \) is small. The linear response of the system to \( V_{ac} \) can be extracted by linearizing Eq. [7] and [10] (see details in Supplemental Material [42]). In Fig. 4 we plot normalized amplitudes of the differential conductance \( |dI/dV|/G_{ex} \), where \( G_{ex}(V_{dc}) \) is the dc exciton conductance \( G_{ex} \). In the low and high frequency limits, the system behaves effectively as a capacitor with \( C_{rf} = \alpha_0 C_{DL}, C_{high} = \alpha_\infty C_{DL} \), where \( \gamma = (1 + 2\gamma_{geo}/C_Q)d_{tot}/d_{DL} \) and \( \alpha_0 \equiv [(\gamma - 1)^2/(1 + \beta \gamma - 1)]/\gamma \) and \( \alpha_{\infty} = 1/\gamma \). \( C_Q = \sqrt{2\pi \hbar \epsilon/(\sqrt{\pi} e^2) \nu^2} \) is the quantum capacitance of graphene [43]. \( dI/dV \) deviates from linear frequency dependence when the scaled frequency \( x = \omega C_{DL}/G_{ex} \sim x_0 = [(1 + \beta \gamma - 1)]/\gamma \). Measuring the crossover frequency \( \nu_0 \), gives the tunneling conductance \( G_{ex} = \omega_0 C_{DL}/x_0 \). The dc bias voltage dependence of the differential conductance is shown in Fig. 4(b). For \( \beta < 0 \) a peak appears at \( V_{peak} = -\mu_{ex}^0/\beta \), the point at which \( n_S \) reaches 0, as mentioned above. This suggests a way to measure the exciton exchange-correlation energy parameter \( g_{XC} \), provided that \( E_\gamma \) and \( E_b \) are known. For \( \beta > 0 \), the differential conductance increases slowly with increasing \( V_b \) in the regime \( V_b > V_{th} \).

Optical recombination, which provides a mechanism for excitons to leak out of the system of interest, can easily be added to the theory explained here, and in the dc bias voltage case converts the equilibrium exciton fluid into a steady state. When the steady state exciton fluid condenses, it will emit coherent light forming a state similar to a polariton laser but subject to precise electrical control.

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[23] For systems in which dark excitons (excitons with momentum or spin quantum numbers that don’t match those of the photons) are favored however, direct optical access is blocked.
[42] See Supplemental Material for the discussion of the total energy functional $E[n,\gamma_\text{ex}]$, the existence of a global minimum and a detailed derivation of the $ac$ response equations.