Exciton–Polaritons in Artificial Lattices and Electron Transport in Bose-Fermi Hybrid Systems

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June 18, 2020 via Zoom

Institute for Basic Science

Center for Theoretical Physics of Complex Systems

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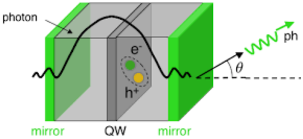
Overview

Exciton–Polaritons in Artificial Lattices

Introduction

$$|Polariton\rangle = \alpha\,|Photon\rangle + \beta\,|Exciton\rangle$$



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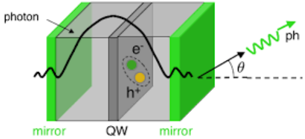

A strong coupling between exciton and photon in microcavities

$$\begin{aligned} H_{pol} &= E_{cav}\hat{a}_k^\dagger \hat{a}_k + E_{exc}\hat{b}_k^\dagger \hat{b}_k \\ &+ \frac{\Omega}{2}\left(\hat{a}_k^\dagger \hat{b}_k + \hat{a}_k \hat{b}_k^\dagger\right) \end{aligned}$$

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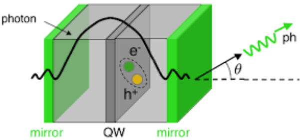

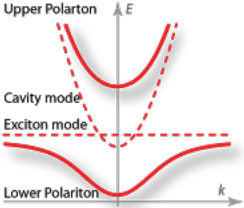

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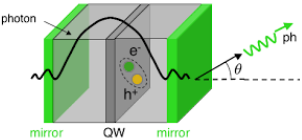

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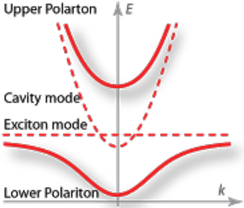

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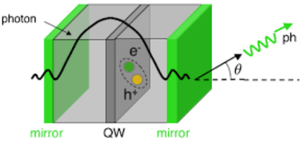

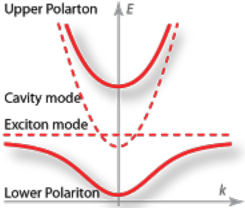

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- Nice coherence properties

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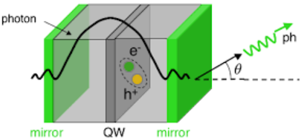

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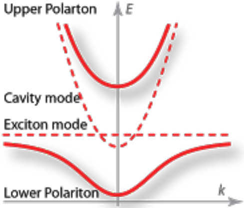

- High critical temperature T_c
- Nice coherence properties
- Strong Nonlinear interaction

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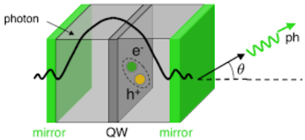

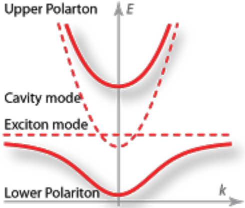

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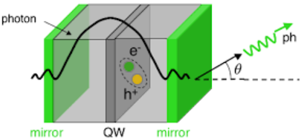

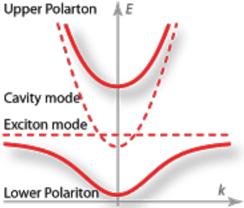

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- High critical temperature T_c
- Nice coherence properties
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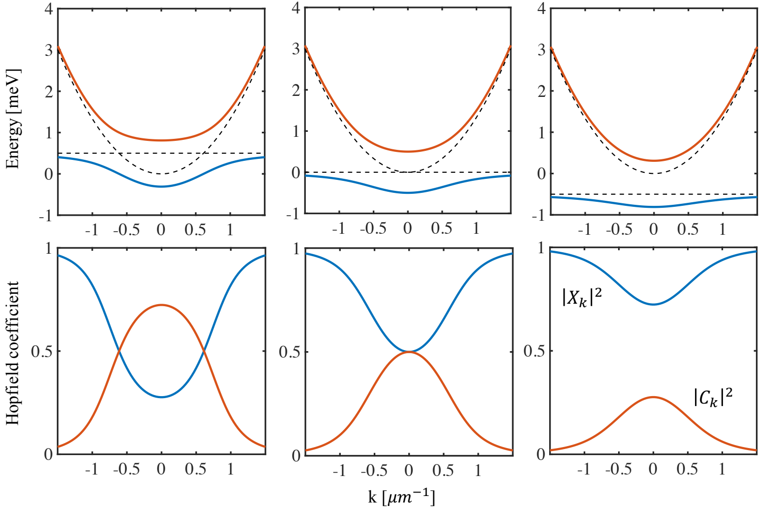
- Driven-dissipative system
- Detunable

Detuning

Detune parameter: $\delta = E_{cav}(k=0) - E_{exc}(k=0)$



With the large scale of de Broglie wavelength, exciton-polaritons can be manipulated by micro-scale potentials.

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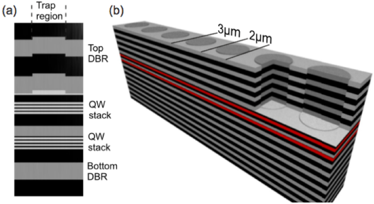
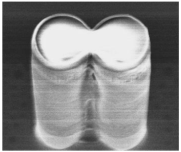
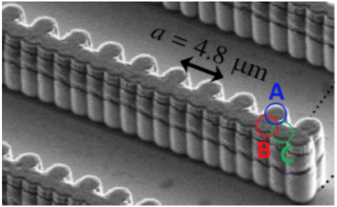
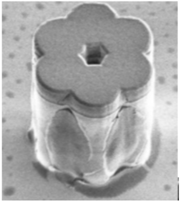
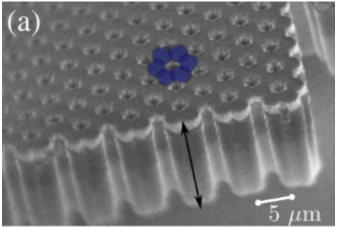
Pics from *Phys. Rev. B, 93:121303 (2016)*, *Phys. Rev. Lett., 116:066402 (2016)* and *Phys. Rev. Lett., 112:116402 (2014)*.











With the large scale of de Broglie wavelength, exciton-polaritons can be manipulated by micro-scale potentials.

Works Include:

- Multivalley condensation [1]
- Phase selection and solitons [2]
- Flat band condensation [3, 4]
- Topological insulator [5]

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The driven-dissipative Gross–Pitaevskii equation:

$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) &= \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}) + \alpha|\psi(\mathbf{r},t)|^2 - \frac{i\gamma}{2}\right]\psi(\mathbf{r},t) \\
&+ \frac{i}{2}R\eta_R(\mathbf{r},t)\psi(\mathbf{r},t) + iP(\mathbf{r},t), \\
\frac{\partial}{\partial t}\eta_R(\mathbf{r},t) &= I(\mathbf{r},t) - R\eta_R(\mathbf{r},t)|\psi(\mathbf{r},t)|^2 - \gamma_R\eta_R(\mathbf{r},t).
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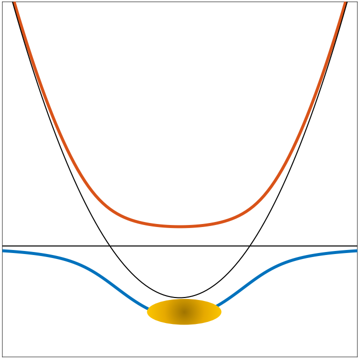

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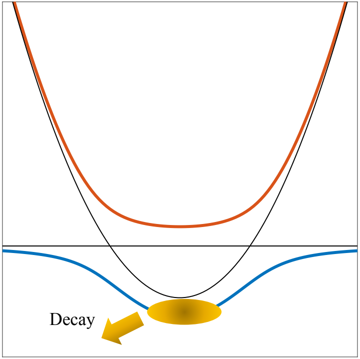

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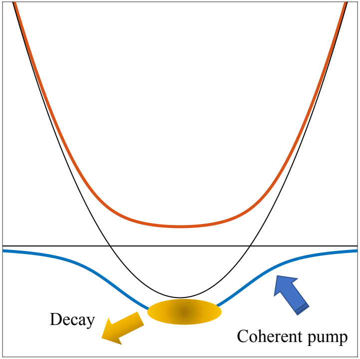

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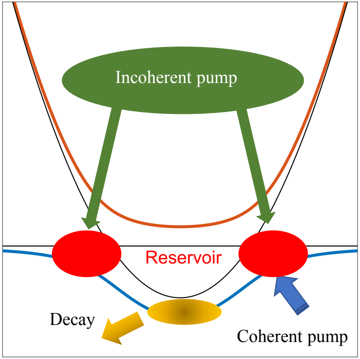

Exciton–Polaritons in Artificial Lattices

Phase Selection and Solitons [2]

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m^*}\partial_x^2\psi + V(x)\psi + (\alpha - i\beta)|\psi|^2\psi$$

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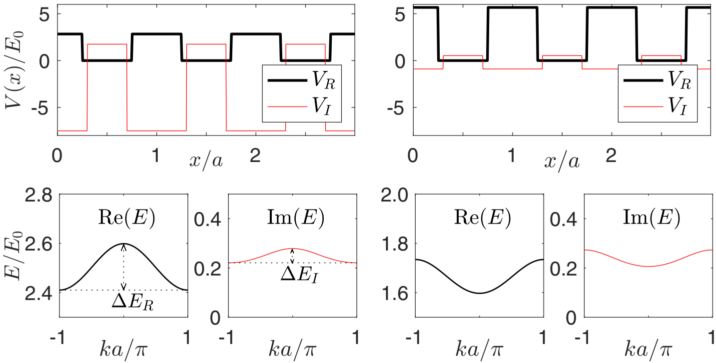

(a) $\Lambda\Lambda$-type (b) VV-type

$\Lambda\Lambda$-type

$$\frac{\alpha}{\beta} = 0 \qquad \frac{\alpha}{\beta} = 2 \qquad \frac{\alpha}{\beta} = 6$$

ΛΛ-type

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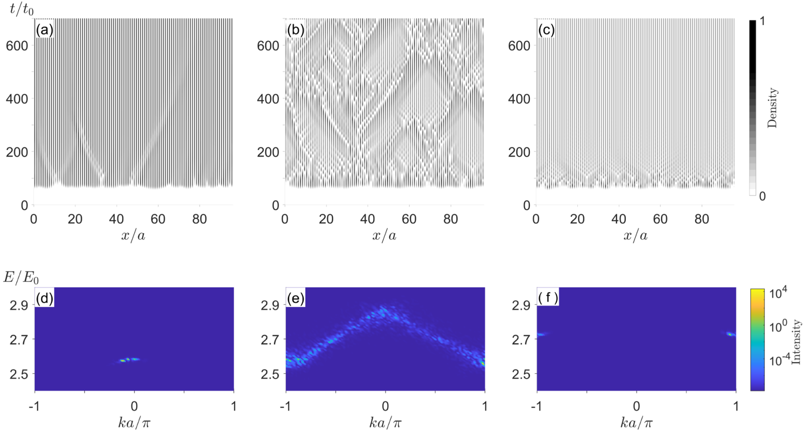
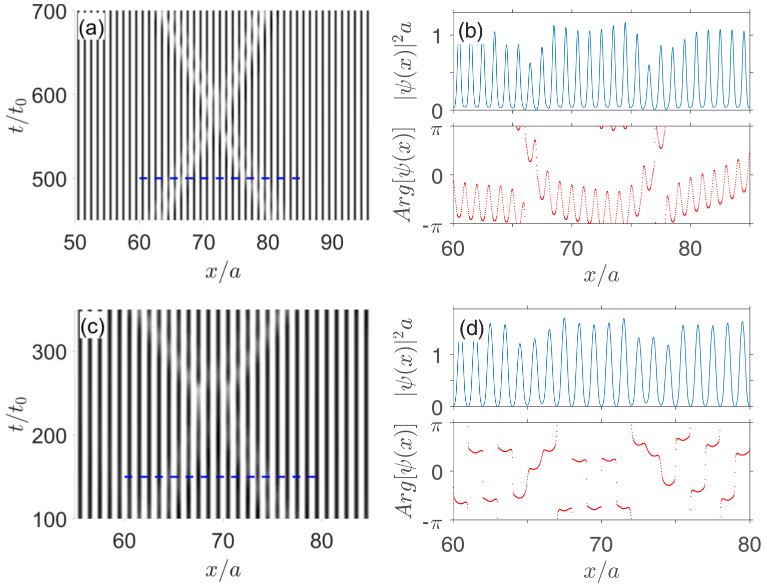
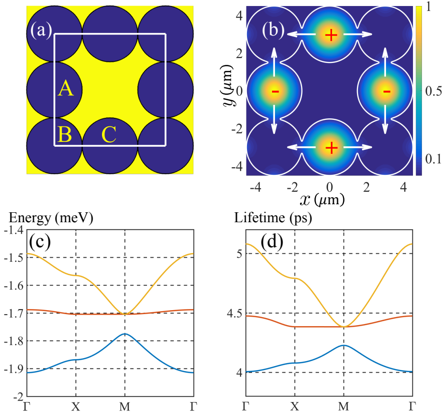


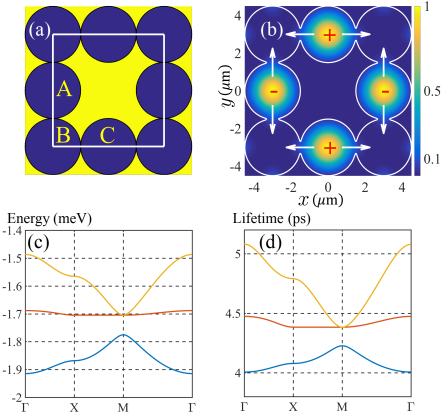

(a)
700
600
500
t/t_0
50
60
70
80
90
x/a
(b)
1
0
$|\psi(x)|^2 a$
π
0
$-\pi$
$Arg[\psi(x)]$
60
70
80
x/a
(c)
300
200
100
t/t_0
60
70
80
x/a
(d)
1
0
$|\psi(x)|^2 a$
π
0
$-\pi$
$Arg[\psi(x)]$
60
70
80
x/a

Exciton–Polaritons in Artificial Lattices

Localiezd condensates in Lieb lattice [3]


(a)
A
B
C
(b)
y (μm)
x (μm)
4
2
0
-2
-4
1
0.5
0.1
+
-
Energy (meV)
(c)
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
Γ
X
M
Lifetime (ps)
(d)
5
4.5
4

$$\hat{H} = \begin{pmatrix} -\frac{\nabla^2}{2m_c} + V(\mathbf{r}) & \Omega \\ \Omega & \delta - \frac{i}{2\tau_x} - \frac{\nabla^2}{2m_x} + \alpha_x|\chi|^2 \end{pmatrix}$$



$$P(\mathbf{r}, t) = P_0 \frac{(x \pm iy)^2}{R^2} \exp\left[-\frac{r^2}{R^2} - i\omega_0 t\right] \theta(t)\theta(t_p - t).$$

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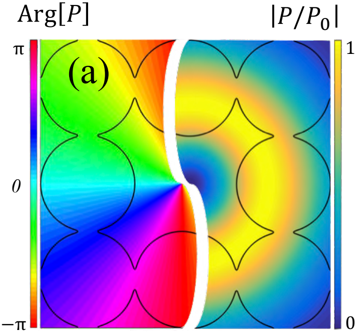
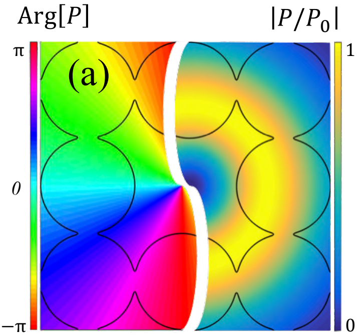


$$i \begin{pmatrix} \dot{\varphi} \\ \dot{\chi} \end{pmatrix} = \hat{H} \begin{pmatrix} \varphi \\ \chi \end{pmatrix} + \begin{pmatrix} iP(\mathbf{r}, t) \\ 0 \end{pmatrix}.$$



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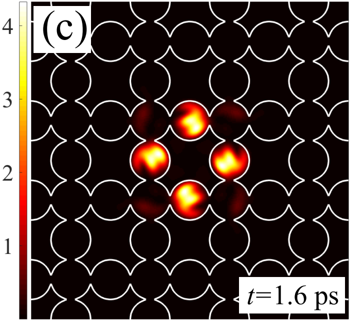
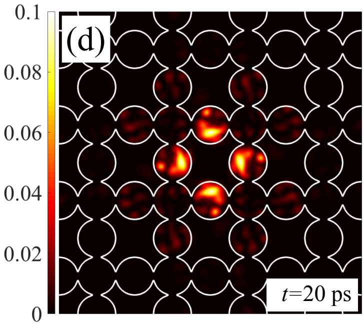


$$i\begin{pmatrix}\dot{\varphi}\\ \dot{\chi}\end{pmatrix} = \hat{H}\begin{pmatrix}\varphi\\ \chi\end{pmatrix} + \frac{icn_r}{2}\begin{pmatrix}0\\ \chi\end{pmatrix} + \begin{pmatrix}iP(\mathbf{r},t)\\ 0\end{pmatrix},$$

$$\frac{\partial n_r}{\partial t} = I - \tau_r^{-1} n_r - c|\chi|^2 n_r.$$



Electron Transport in Bose-Fermi Hybrid Systems

Bogolon–Mediated Electron Scattering [6, 7]

- A layer of fermions (graphene or normal metal)
- A layer of bosons in condensate (indirect-exciton)
- Columb interaction between fermion and boson layers

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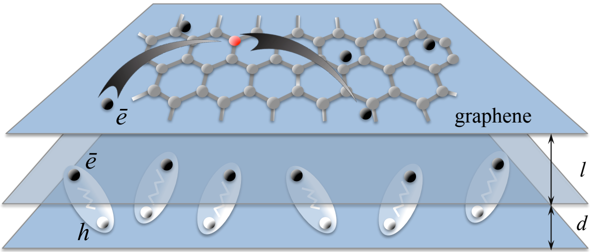
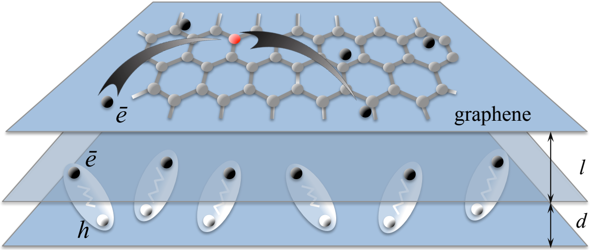


$$
\begin{aligned}
g(r) &= \frac{e_0^2}{4\pi\epsilon}\left(\frac{1}{r_{ee}} - \frac{1}{r_{eh}}\right) \\
g(k) &= \frac{e_0^2}{2k\epsilon} e^{-kl}\left(1 - e^{-kd}\right)
\end{aligned}
$$



Electron-exciton interaction

$$V = \int d\mathbf{r} \int d\mathbf{R} \Psi_{\mathbf{r}}^{\dagger} \Psi_{\mathbf{r}} g\left(\mathbf{r} - \mathbf{R}\right) \Phi_{\mathbf{R}}^{\dagger} \Phi_{\mathbf{R}}$$

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Exictons in BEC

$$\Phi_{\mathbf{R}} = \sqrt{n_c} + \phi_{\mathbf{R}}$$

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Exictons in BEC

$$\Phi_{\mathbf{R}} = \sqrt{n_c} + \phi_{\mathbf{R}}$$

$$\begin{aligned} V_1 &= \sqrt{n_c} \int d\mathbf{r} \Psi_{\mathbf{r}}^{\dagger} \Psi_{\mathbf{r}} \int d\mathbf{R} g\left(\mathbf{r}-\mathbf{R}\right) \left[\phi_{\mathbf{R}}^{\dagger} + \phi_{\mathbf{R}}\right] \\ V_2 &= \int d\mathbf{r} \Psi_{\mathbf{r}}^{\dagger} \Psi_{\mathbf{r}} \int d\mathbf{R} g\left(\mathbf{r}-\mathbf{R}\right) \phi_{\mathbf{R}}^{\dagger} \phi_{\mathbf{R}} \end{aligned}$$

Bogoliubov transformation

$$\phi_p = u_p b_p + v_p b^\dagger_{-p}, \quad \phi^\dagger_p = u_p b^\dagger_p + v_p b_{-p}$$

$$u_p^2 = 1 + v_p^2 = \frac{1}{2}\left(1 + \sqrt{1 + \frac{M^2 s^4}{\omega_p^2}}\right), \quad u_p v_p = -\frac{Ms^2}{2\omega_p}$$

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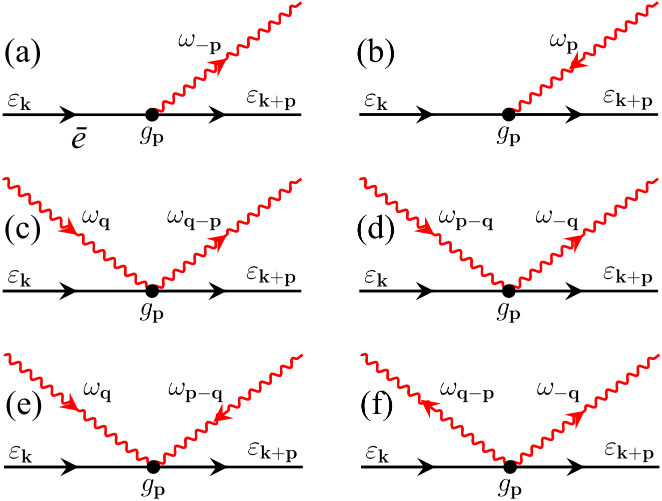
One- and two-bogolon interaction

$$\begin{aligned} V^{(1)} &= \frac{\sqrt{n_c}}{L} \sum_{\mathbf{k},\mathbf{p}} g_{\mathbf{p}} \left[(v_{\mathbf{p}} + u_{-\mathbf{p}})\, b^\dagger_{-\mathbf{p}} + (u_{\mathbf{p}} + v_{-\mathbf{p}})\, b_{\mathbf{p}} \right] c^\dagger_{\mathbf{k}+\mathbf{p}} c_{\mathbf{k}} \\ V^{(2)} &= \frac{1}{L^2} \sum_{\mathbf{k},\mathbf{p},\mathbf{q}} g_{\mathbf{p}} \Big[u_{\mathbf{q}-\mathbf{p}} u_{\mathbf{q}} b^\dagger_{\mathbf{q}-\mathbf{p}} b_{\mathbf{q}} + u_{\mathbf{q}-\mathbf{p}} v_{\mathbf{q}} b^\dagger_{\mathbf{q}-\mathbf{p}} b^\dagger_{-\mathbf{q}} \\ &+ v_{\mathbf{q}-\mathbf{p}} u_{\mathbf{q}} b_{-\mathbf{q}+\mathbf{p}} b_{\mathbf{q}} + v_{\mathbf{q}-\mathbf{p}} v_{\mathbf{q}} b_{-\mathbf{q}+\mathbf{p}} b^\dagger_{-\mathbf{q}} \Big] c^\dagger_{\mathbf{k}+\mathbf{p}} c_{\mathbf{k}} \end{aligned}$$


(a)
$\omega_{-\mathbf{p}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$\bar{e}$
$g_{\mathbf{p}}$
(b)
$\omega_{\mathbf{p}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$g_{\mathbf{p}}$
(c)
$\omega_{\mathbf{q}}$
$\omega_{\mathbf{q-p}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$g_{\mathbf{p}}$
(d)
$\omega_{\mathbf{p-q}}$
$\omega_{-\mathbf{q}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$g_{\mathbf{p}}$
(e)
$\omega_{\mathbf{q}}$
$\omega_{\mathbf{p-q}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$g_{\mathbf{p}}$
(f)
$\omega_{\mathbf{q-p}}$
$\omega_{-\mathbf{q}}$
$\varepsilon_{\mathbf{k}}$
$\varepsilon_{\mathbf{k+p}}$
$g_{\mathbf{p}}$

Boltzmann equation

$$e_0 \mathbf{E} \frac{\partial f}{\hbar \partial \mathbf{p}} = I\{f\}$$

Boltzmann equation

$$e_0 \mathbf{E} \frac{\partial f}{\hbar \partial \mathbf{p}} = I\{f\}$$

Collision integral

$$\begin{aligned} I\{f\} \quad = \quad & -\frac{1}{\hbar} \int \frac{d\mathbf{q} d\mathbf{p}'}{(2\pi)^2} |V_q^{(1)}|^2 \\ & \times \Big[N_q f_p (1 - f_{p'}) \delta(\varepsilon_p - \varepsilon_{p'} + \hbar\omega_q) \delta(\mathbf{p} - \mathbf{p}' + \mathbf{q}) \\ & + (N_q + 1) f_p (1 - f_{p'}) \delta(\varepsilon_p - \varepsilon_{p'} - \hbar\omega_q) \delta(\mathbf{p} - \mathbf{p}' - \mathbf{q}) \\ & - N_q f_{p'} (1 - f_p) \delta(\varepsilon_{p'} - \varepsilon_p + \hbar\omega_q) \delta(\mathbf{p}' - \mathbf{p} + \mathbf{q}) \\ & - (N_q + 1) f_{p'} (1 - f_p) \delta(\varepsilon_{p'} - \varepsilon_p - \hbar\omega_q) \delta(\mathbf{p}' - \mathbf{p} - \mathbf{q}) \Big] \end{aligned}$$

Boltzmann equation

$$e_0 \mathbf{E} \frac{\partial f}{\hbar \partial \mathbf{p}} = I\{f\}$$

Weak electric field

$$f = f^0\left(\varepsilon_p\right) + \left(\frac{\partial f^0}{\partial \varepsilon_p}\right) \phi_p$$

$$\phi_p = e_0 E_x \tau\left(\varepsilon_p\right) \frac{\partial \varepsilon_p}{\hbar \partial p_x}$$

Boltzmann equation

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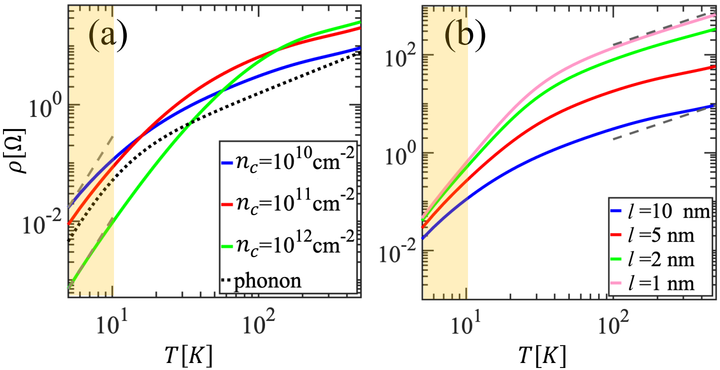
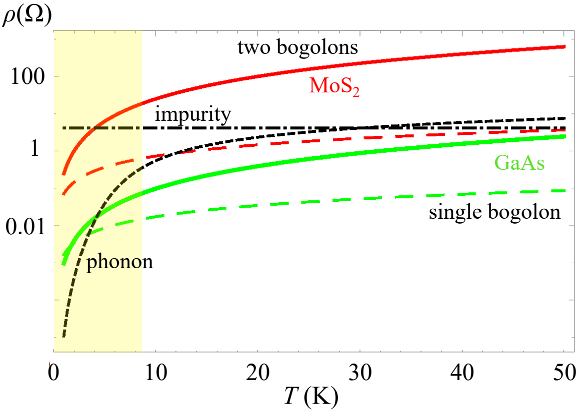
Resistivity

$$\rho^{-1} = e_0^2 \mathcal{D}(\varepsilon_f) \frac{v_f^2}{2} \langle \tau \rangle$$

$$\rho \propto T^4 \; (T \ll T_{BG}), \qquad \rho \propto T^1 \; (T \gg T_{BG})$$

$$T_{BG} = \frac{2\hbar s k_f}{k_B}$$




$\rho(\Omega)$
100
1
0.01
two bogolons
MoS$_2$
impurity
GaAs
single bogolon
phonon
0
10
20
30
40
50
T (K)

Phase selection

- Condensate: $0-$phase $\Leftrightarrow$ $\pi-$phase
- Dark soliton

Lieb lattice

- Exciton-polariton dispersion in Lieb lattice
- Excite the CLS

Hybrid system

- Temperature dependent resistivity
- Two-bogolon dominant in parabolic case

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T h a n k
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