Quantum Bus of Metal Nanowire with Surface Plasmon Polaritons

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(Dated: April 16, 2010)

Abstract

We develop an architecture for distributed quantum computation using quantum bus of plasmonic circuits and spin qubits in self-assembled quantum dots. Deterministic quantum gates between two distant spin qubits can be reached by using an adiabatic approach in which quantum dots couple with highly detuned plasmon modes in a metallic nanowire. Plasmonic quantum bus offers a robust and scalable platform for quantum optics experiments and the development of on-chip quantum networks composed of various quantum nodes, such as quantum dots, molecules and nanoparticles.

PACS numbers: 03.67.-a, 32.80.-t, 42.50.Pq, 73.20.Mf
Plasmonic circuits, providing the ability to integrate electronics and optics on the nanoscale, may lead an exciting application to carry classical information between microprocessors in integrated chip [1]. For a scalable quantum chip, it is also desired to find a high speed on-chip quantum bus where the information can be coherently transferred between distant processing nodes. Integrated plasmonic circuits are an attractive route towards realizing such promise since they allow for scalability and coherent coupling to single emitters [2–5]. Recently, self-assembled quantum dots are argued as a promising candidate for building a practical quantum processor for their potential advantages, including self-evident scaling, ultra-fast coherent control and long lived spin states [6–9]. Picosecond optical coherence measurement, preparation and manipulation of electron spin states have been demonstrated in self-assembled quantum dot systems [10–12]. However, most of the proposals for coherent coupling of two spin qubits are based on the interactions between neighboring dots [13, 14]. A solution is expected to utilize quantum bus to couple qubits in a non-local and switchable way. Here we show the implementation of a quantum bus, using the surface plasmon polaritons confined in the metallic nanowires, to coherently couple an arbitrary pair of distant semiconductor quantum dot spin qubits. The interaction is mediated by the exchange of virtual surface plasmon polaritons rather than real ones, avoiding the decoherence of the system. Using adiabatic control of the qubits, we demonstrate high fidelity quantum operations between spatially separated spin qubits. Our approach is applicable to a wide class of electronic spin qubits near the nanowire and can be used for the implementation of distributed quantum computing architectures.

Fig. 1 shows our scalable solid state quantum computer architecture, in which spins in self-assembled quantum dots (QDs) act as qubits. These QDs can be grown by molecular beam epitaxy along the z axis. Single electron can be deterministically injected to QD by the semi-transparent metallic gate. Each QD is selectively coupled to a laser field guided by a nanotip and a fiber taper which has been realized in recent experiment [15]. The coupling between QDs is mediated by surface plasmon modes in metallic nanowire. Throughout, we use a silver nanowire with electric permittivity $\varepsilon_2 = -50 + 0.6i$ at room temperature and a vacuum wavelength $\lambda_0 = 950$ nm [16], and the surrounding dielectric $\varepsilon_1 = 2$ (the nanowire is covered with a thin layer of PMMA). We assume a large oscillator strength QDs $f = 100$ which corresponds lateral radius of around 22nm [17]. In the following, we discuss the quantization of surface plasmons in metal nanostructure and then give the detailed coupling mechanism between QD spin and plasmon.
FIG. 1: (a) The hybrid platform to implement quantum information processing. In this architecture, non-local spins in self-assembled quantum dots (QDs) are interconnected via quantum bus of surface plasmons (red wave line) in metal nanowire. Single electron can be deterministically injected to QD by static gate. The qubit is individually addressed using a laser guided by a nanotip and a fiber taper. (b) The levels of a charged quantum dot. The spin state $| \uparrow \rangle$ is coupled to an optically excited trion state $| \uparrow \downarrow \rangle$ by plasmon modes and laser pulse.

Surface plasmons, or surface plasmon polaritons are generally treated as classical electromagnetic waves that propagate along surface of a conductor. Recent experiment has shown that the fluorescence of quantum dots can be coupled to metallic nanowires and single, quantized plasmon can be generated [4]. In this work, we present a fully quantum mechanical approach for the interaction between electron spin in QD and quantized plasmon in the nanowire. In a cylindrical nanowire, the solution to electromagnetic modes has been given in Ref. [18, 19] for quite some time. The energy of the surface plasmon field is the sum of the kinetic and electrostatic energy

$$H = \frac{1}{2} \int \{ n_0 m_e (\nabla \Psi_s)^2 + \rho_s \Phi_s \} d^3 r,$$

where $n_0$ is the equilibrium electron density in the metal, $m_e$ is the electron mass, $\Psi_s(r)$ is the velocity potential, $\rho_s(r)$ is the charge density displacement from equilibrium, and $\Phi_s(r)$
is the scalar potential at the surface. The velocity potential $\Psi_s(r)$ and electronic density displacement $n_s(r)$ satisfies the continuity equation

$$\partial_t n_s = n_0 \nabla^2 \Psi_s. \hspace{3cm} (2)$$

For a cylindrical nanowire of radius $R$ and length $L$, the velocity potential and electrical potential can be expanded in cylindrical coordinates

$$\Psi_s(r) = \sum_{k,m} a_{k,m} K_m(k\rho) e^{i(kz+m\phi)}, \Phi_s(r) = \sum_{k,m} c_{k,m} K_m(k\rho) e^{i(kz+m\phi)}, \text{for } \rho > R, \hspace{3cm} (3)$$

$$\Psi_s(r) = 0, \Phi_s(r) = \sum_{k,m} b_{k,m} I_m(k\rho) e^{i(kz+m\phi)}, \text{for } \rho < R, \hspace{3cm} (4)$$

and the electronic density is correspondingly expressed as

$$n_s(r) = \sum_{k,m} n_{k,m} e^{i(kz+m\phi)} \delta(\rho - R), \hspace{3cm} (5)$$

where $I_m(x)$ and $K_m(x)$ are the cylindrical Bessel functions. Applying Maxwell’s boundary conditions, the relations between the coefficients $a_{k,m}$, $b_{k,m}$, $c_{k,m}$ and $n_{k,m}$ can be determined.

With the electromagnetic field quantization calculations [20], the Hamiltonian of the surface plasmon field Eq. (1) can be expressed in the standard second quantized form

$$H_{pl} = \sum_{k,m} \hbar \omega_{k,m} [a_{k,m} a_{k,m}^\dagger + \frac{1}{2}], \hspace{3cm} (6)$$

where $\omega_{k,m}^2 = \omega_p^2 \frac{k R I_m'(k R) K_m(k R)}{I_m(k R) K_m'(k R)}$, $\omega_p$ is the bulk plasma frequency, $\epsilon_s = 3.3$ is the background dielectric constant of the silver, and $I_m'(x) = dI_m(x)/dx$.

We consider single-charged self-assembled QDs with strong confinement along the growth direction. Because of the large heavy-hole-light-hole splitting, we can neglect the light-hole excitons and the QD can be effectively described by a four-level system, the electron spin states $|\downarrow\rangle$, $|\uparrow\rangle$, and the two trion states consisting of two spin paired electrons and unpaired heavy hole, $|\uparrow\downarrow, \downarrow\rangle$, $|\uparrow\downarrow, \uparrow\rangle$. The qubit is encoded in spin states of the excess electron. The $\sigma^+$ polarized light guided by a metallic nanotip can only connect spin state $|\uparrow\rangle$ to an optically excited trion state $|\uparrow\downarrow, \uparrow\rangle$ as shown in Fig. 1(b). Using the rotating wave approximation, the Hamiltonian between the QD and circularly polarized laser is expressed as

$$H_{laser-QD} = \delta_L |\uparrow\downarrow, \uparrow\rangle \langle\uparrow\downarrow, \uparrow| + \Omega(t)|\uparrow\rangle \langle\uparrow| + \text{h.c.}. \hspace{3cm} (7)$$

Here $\Omega(t)$ is the optical Rabi amplitude due to laser field guided by nanotip, $\delta_L = E_\tau - \nu$, $E_\tau$ is the trion energy, and $\nu$ is the laser frequency.
The interaction between the plasmon field and a QD is given by

$$H_{pl-QD} = -d \cdot E.$$  \hspace{1cm} (8)
specifical wave vector $k$, the detuning is $\delta_{pl} = E_\tau - \omega_0(k)$. From the Eq. (8) and Eq. (9), the coupling strength between the nanowire and QD is found to be

$$g = \hbar C \left[ \frac{1}{4\pi|\epsilon_1 + (\epsilon_s - \epsilon_1)CI^m(C)K_m(C)|\epsilon_0 m_e LR^2 E_\tau K_0(C)} \pi e^2 f \frac{\omega_0}{\omega_0} J_0(C) \right]^{1/2} K_1(k_{||}(R + d)), \quad (10)$$

where $C = k_{||} R$, $e$ is electron charge, $\epsilon_0$ is the vacuum electric constant. The results of coupling strength $g$ against the nanowire radius $R$ and the distance between QD and nanowire edge $d$ with a nanowire length of $L = 10 \mu m$ and a QD of exciton oscillator strength $f = 100$ are shown in Fig. 2.

We have also carried out the detailed numerical simulations using the finite element method (FEM) to verify the analytical results above. We use FEM simulations to obtain the electromagnetic field solution and mode volume of nanowire. In the inset of Fig. 3, we plot the mode profile ($m = 0$) of electric field ($|\epsilon_i E^2_i|$) with a nanowire of $R = 70$ nm and $L = 10 \mu m$, where $i = 1, 2$ and $E_1, E_2$ denote the electric field outside and inside the nanowire respectively. The electromagnetic field presents the reflection and leakage at the end surface of nanowire as shown in the inset, which are not involved in the analytical model. The coupling strength of QD and nanowire interaction is given by $g = \hbar \left[ \frac{1}{4\pi|\epsilon_1 + (\epsilon_s - \epsilon_1)CI^m(C)K_m(C)|\epsilon_0 m_e LR^2 E_\tau K_0(C)} \pi e^2 f \frac{\omega_0}{\omega_0} J_0(C) \right]^{1/2} \tilde{V}$ [22], where $\tilde{V}$ is the plasmon mode volume ($m = 0$). The results of FEM simulations show $g = 0.41$ meV for a nanowire of $R = 20$ nm and $d = 30$ nm, while the coupling constant is $g = 0.49$ meV through Eq. (10). The analytical results are larger than the results given by FEM simulations because of the leakage of electromagnetic field at end surface. To neglect the affect of the leakage of electromagnetic field, we plot the normalized coupling strength $g_N = g(R)/g(R = 20 \text{ nm}, d = 0)$ as a function of $R$ given by both FEM simulations and the analytical derivation respectively in Fig. 3. It is found that the FEM simulation results and analytical derivations agree closely.

The dynamics of the coupled system of QDs and nanowire can be described by the whole Hamiltonian:

$$H = H_{pl} + H_{QD} + H_{pt-QD} + H_{laser-QD} + H_{pl,\kappa} + H_{QD,\gamma}. \quad (11)$$

$H_{pl,\kappa}$ describes the plasmon decay through Landau damping, while $H_{QD,\gamma}$ describes the coupling of QD to Markovian reservoirs. We consider several quantum dots coupled to a metallic nanowire and each dot is irradiated with an identical frequency $\sigma^+$ polarized laser light. In the rotating frame at the laser frequency, the Hamiltonian is given by

$$H(t) = \sum_j [\hat{\delta}_{L,j} |\uparrow\downarrow, \uparrow\rangle_j \langle\uparrow\downarrow, \uparrow| + [(g_j a^+ e^{i\Delta_j t} + \Omega_j(t))] |\uparrow\rangle_j \langle\uparrow\downarrow, \uparrow| + h.c.], \quad (12)$$
FIG. 3: The normalized coupling strengths $g_N$ calculated using FEM simulations are plotted as a function of $R$ at $d = 0$ (line a), $d = 30$ nm (line b) with a nanowire length of $L = 10 \mu$m. Compared with the FEM simulations, the normalized coupling strengths $g_N$ obtained using analytical model are plotted at $d = 0$ (line c), $d = 30$ nm (line d) with a nanowire length of $L = 10 \mu$m. Inset: the electric field profile $|\varepsilon_i E_i|^2$ of the fundamental mode of a nanowire with $R = 70$ nm and $L = 10 \mu$m is calculated using FEM simulations.

where $\Delta_j = \delta_{L,j} - \delta_{pl,j}$.

To explore the applications of the plasmonics based quantum bus, we consider the implementation of a controlled-phase (CPHASE) gate between two distant spin qubits ($i$-th and $j$-th qubits). The adiabatic control is applied to avoid the trion spontaneous emission and the plasmon decay. We use a laser pulse with slowly changing Gaussian field amplitude $\Omega(t) = \Omega_0 e^{-(t^2/\tau^2)}$ and a constant detuning. The evolution operator due to the adiabatic pulse is $U(t, t_0) \equiv T \exp \left\{ -\frac{i}{\hbar} \int_{t_0}^{t} H(t') dt' \right\}$. Each phase change of the four computational basis states $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ depends on adiabatic phase shift of single qubit $\theta_i$ and nonlinear phase shift of both qubits $\phi_{ij}$. Assume that the plasmon field is initially in the vacuum state. If the optical pulse of amplitude is large enough to create a gate phase $\theta_{i,j} = \phi_{00} - \phi_{01} - \phi_{10} + \phi_{11} = 2 \text{Re} \left\{ \int dt \frac{\Omega_i(t) \Omega_j(t) g_i g_j^*}{\delta_i \delta_j \Delta} \right\} = \pi$, a gate locally equivalent to the CPHASE gate is achieved [23]. Up to a basis change of the target qubit and a phase shift on the control qubit, CPHASE gate is equivalent to controlled-not (CNOT) gate.

To estimate the performance of plasmonic quantum bus, we follow the standard quantum
theory of damping to calculate CPHASE gate fidelity in Markovian approximation. The master equation for QDs and nanowire system can be described by

\[ \frac{d\rho}{dt} = -i[H_s, \rho] - \frac{\kappa}{2}(a^\dagger a \rho + \rho a^\dagger a - 2a^\dagger a \rho) + \sum_i D[L_i] \rho, \tag{13} \]

where \( \rho = \rho_s \otimes \rho_{pl} \) is density matrix of two qubits and nanowire coupled system, \( H_s = H_{pl} + H_{QD} + H_{pl-QD} + H_{laser-QD} \), \( D[L_i] \rho = L_i \rho L_i^\dagger - \frac{1}{2}(L_i^\dagger L_i \rho + \rho L_i^\dagger L_i) \) and \( L_i \) describes the trion decay effect induced by various scattering channels such as phonon environment and radiation field. For self-assembled InGaAs QDs, the key decoherence parameter is trion radiative recombination time which is about 0.1 ns. On the other hand, the effective lifetime of surface plasmon modes is \( \frac{(\Delta^2/\Omega^2(t))(\delta/g)^2}{\kappa} \), where \( \kappa \) is the decay rate of surface plasmon in nanowire. We consider two qubits initialized into the \( |\psi\rangle = (|00\rangle - |01\rangle - |10\rangle + |11\rangle)/2 \). Applying adiabatic Gaussian pulses with \( \tau = \sqrt{\pi/2\delta L_i \delta^* L_j \Delta/(\Omega^2 g_i g_j)} \) on both qubits, the output density matrix is \( \rho \) following the master equation (13) after the gate. The fidelity is defined as \( F = \text{Tr}[\sqrt{\rho \rho' \sqrt{\rho}}] \), where the \( \rho' \) is the output density matrix following the master equation without decay terms. We calculated numerically the fidelity of CPHASE gate of two distant qubits versus the decay rate of the trion state \( \Gamma \) and the quality factor of the plasmonic cavity \( Q \) with optimum \( \delta L \) and \( \Delta \) under the adiabatic approximation, as shown in Fig. 4. It is shown that, for \( \Gamma = 0.01 \) ps\(^{-1} \) and \( Q = 1000 \), the fidelity of the two-qubit gate can be 97%. The high-Q plasmonic microcavities \( Q > 1000 \) have been reported in recent experiment [24]. Thus, high fidelity operations of two-qubit gate can be achieved between two separated spin qubits coupled via quantum bus of plasmon circuits.

We finally discuss potential realizations of distributed quantum computing architectures which are based on plasmon mediated nonlocal spin-spin interactions [25]. In the hybrid platform, each node which consists of a nanowire and a few physical qubits, connects to a QD acting as a transceiver qubit and all the transceiver qubits are coupled via a plasmonic circuit or dielectric waveguide [5]. A key technique to implement distributed quantum computing is performing a nonlocal CNOT gate between qubit A in the \( i \)-th node and qubit B in the \( j \)-th node. We firstly apply polarized laser pulses on both \( i \)-th and \( j \)-th transceiver qubits to prepare the qubits to be Einstein-Podolsky-Rosen state \( (|\downarrow_i \rangle |\uparrow_j \rangle - |\uparrow_i \rangle |\downarrow_j \rangle)/\sqrt{2} \). After a set of sequential operations including CNOT gate between qubit A and \( i \)-th transceiver qubit, CNOT gate between qubit B and \( j \)-th transceiver qubit, single qubit measurement and operation [26], the nonlocal CNOT gate between qubit A and qubit B is completed.

In summary, we develop a novel and scalable method to controllably couple any distant electron spins in self-assembled quantum dots via surface plasmon based quantum bus. A
FIG. 4: Fidelity of CPHASE gate of two distant qubits as function of the decay rate of the trion state $\Gamma$ and the quality factor of the plasmonic cavity $Q$ with optimum $\delta_L$ and $\Delta$, calculated numerically under the adiabatic approximation.

A fully quantum mechanical approach is introduced to describe the interaction between surface plasmon polariton of metal nanowire and quantum dot spins. Virtual plasmon excitation is exploited to overcome the decoherence of the system and a switchable long range interaction is achieved between spin qubits. The proposed architecture is an attractive approach for distributed quantum computation in a chip and realizable by the present standard solid state chip technology.

Acknowledgement This work was supported by the National Basic Research Program of China (Grants No. 2009CB929600, No. 2006CB921900), the National Natural Science Foundation of China (Grants No. 10804104, No. 10874163, No. 10604052) and the State Key Program of the National Natural Science Foundation of China (Grants No. 10934006).

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