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# Towards hybrid circuit quantum electrodynamics with quantum dots

## *Vers une électrodynamique quantique en cavité sur puce avec des boîtes quantiques*

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ABSTRACT

Cavity quantum electrodynamics allows one to study the interaction between light and matter at the most elementary level. The methods developed in this field have taught us how to probe and manipulate individual quantum systems like atoms and superconducting quantum bits with an exquisite accuracy. There is now a strong effort to extend further these methods to other quantum systems, and in particular hybrid quantum dot circuits. This could turn out to be instrumental for a noninvasive study of quantum dot circuits and a realization of scalable spin quantum bit architectures. It could also provide an interesting platform for quantum simulation of simple fermion–boson condensed matter systems. In this short review, we discuss the experimental state of the art for hybrid circuit quantum electrodynamics with quantum dots, and we present a simple theoretical modeling of experiments.



RÉSUMÉ

L'électrodynamique quantique en cavité permet d'étudier l'interaction lumière–matière au niveau le plus fondamental. Les méthodes développées dans ce domaine permettent de sonder des systèmes quantiques modèles, comme les atomes ou les bits quantiques supraconducteurs, avec une précision inégalée. Ces succès ont motivé un effort pour étendre ces techniques à d'autres systèmes quantiques, notamment aux circuits hybrides à base de boîtes quantiques. Le couplage de cavités micro-ondes à de tels systèmes pourrait déboucher sur des caractérisations non invasives des boîtes quantiques, sur la réalisation de bits quantiques de spin à grande échelle, ou sur l'élaboration d'une plateforme de simulation quantique de systèmes spin–bosons en matière condensée. Nous présentons

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dans ce court article de revue un état de l'art expérimental, et introduisons une description théorique simple des systèmes hybrides à base de boîtes quantiques développés pour l'électrodynamique en cavité.



## 1. Interest of the use of cQED techniques

Using an oscillator as a detector to readout the state of a system coupled with it is a widely used method in classical and quantum physics. Some of the most renowned example include Atomic Force Microscopy [1], Nuclear Magnetic Resonance spectroscopy [2] or mass sensing. In circuit quantum electrodynamics (*cQED*), these resonators can be in the quantum regime with discrete photon states interacting with mesoscopic circuits. For devices such as quantum dots, the high-frequency capacitive measurement offered by superconducting resonators is to be compared to the usual electronic transport techniques. In contrast with conductance measurements, it provides a fast and non-invasive detection and allows measurements of devices with extremely small couplings with leads, thus avoiding decoherence caused by coupling with fermionic reservoirs. This issue was previously overcome using techniques such as radio-frequency charge sensing [3]. However, high-finesse, high-frequency (GHz) resonators go beyond and naturally provide a high sensitivity and high-speed measurements. Working at high frequencies also allows one to measure effects related to quantum capacitance [4,5], or investigate electronic transitions resonant with the cavity. By avoiding transport, cQED readout techniques could yield to QND [6,7] (quantum non-demolition) measurements of charge or spin states in quantum dot devices. Another significant potential of cQED architectures is the scalability, which, combined with recently demonstrated spin–photon coupling [8], could allow us to tackle fundamental problems such as the coupling and entanglement of distant spins [9–16]. Finally, because modern nano-fabrication techniques, in general, allow one to build devices with arbitrary complexity, cQED provides a conciliating platform to go towards hybrid systems that combine different types of quantum degrees of freedom and their respective advantages. Superconducting circuits have already been used to couple microwave photons with large spin ensembles [17,18], magnons [19], but also mechanical resonators [20,21], or optical photons [22].

## 2. Technical realization of hybrid circuit quantum electrodynamics devices with quantum dots

The realization of circuit quantum electrodynamics architectures with quantum dot circuits has been enabled by the progress of nanofabrication techniques. This combines low-dimensional conductors with metallic electrodes and superconducting resonators. Quantum dot circuits based on GaAs 2-dimensional electron gases [23], semi-conducting nanowires [24], carbon nanotubes [25], and graphene [26] have already been coupled with cavities. Depending on host materials, fabrication methods vary and present different challenges when it comes to obtaining high-quality factors. For instance, GaAs 2-dimensional electron gases must be kept away from the resonator field to avoid dissipation. GaAs substrates also have piezoelectric properties that can cause microwave loss. Carbon nanotubes require a step of chemical vapor deposition growth at high temperature under a hydrogen atmosphere, and the growth is associated with deposition of amorphous carbon that can cause strong dissipation. Various techniques have thus been developed to circumvent these issues [23,25,26].

## 3. Coupling with individual electronic states in quantum dots

Quantum dot individual states are naturally electrically coupled with the electromagnetic field via their charge density. In a first approach, one may use a circuit diagram as in Fig. 1 to explain how the quantum dot interacts with the field trapped in a transmission line resonator. The quantum dot capacitance $C_{\text{dot}}$ is typically of the order of the $aF$. The total inductance $L_{\text{res}}$ of the transmission line and its total capacitance $C_{\text{res}}$ to the ground are typically $L_{\text{res}} \approx 0.5$ nH and $C_{\text{res}} \approx 1$ pF (see, e.g., [27]). A small change in $C_{\text{res}}$ due to the quantum dot total capacitance leads to a change in $f_c$ by $\Delta f_c$, i.e.

$$f_c + \Delta f_c = \frac{1}{2\pi\sqrt{L_{\text{res}}(C_{\text{res}} + \Delta C_{\text{dot}})}} \approx f_c \left(1 - \frac{\Delta C_{\text{dot}}}{2C_{\text{res}}}\right) \tag{1}$$

$$\Delta f_c \approx -\frac{f_c}{2C_{\text{res}}} \Delta C_{\text{dot}} \tag{2}$$

It is always practical to think in terms of an effective dot capacitance in order to evaluate the orders of magnitudes involved in a given experiment. However, one should keep in mind that the picture of Fig. 1 is a strong approximation since quantum dots circuits are in general non-linear systems that can for instance be used to obtain a lasing effect (see section 6.4).

Microscopically, the coupling between a simple quantum dot circuit (with no loops) and a cavity can be described by incorporating an electric potential term in the cavity+dot Hamiltonian [28]:

$$H_{\text{dot–cavity}} = e \int d^3r\, \hat{\rho}(r)\, v(r)\, V_{\text{rms}}(a + a^\dagger) \tag{3}$$