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Towards scaling up trapped ion quantum information processing

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Abstract Recent theoretical advances have identified several computational algorithms that can be implemented utilizing quantum information processing (QIP), which gives an exponential speedup over the corresponding (known) algorithms on conventional computers. QIP makes use of the counter-intuitive properties of quantum mechanics, such as entanglement and the superposition principle. Unfortunately it has so far been impossible to build a practical QIP system that outperforms conventional computers. Atomic ions confined in an array of interconnected traps represent a potentially scalable approach to QIP. All basic requirements have been experimentally demonstrated in one and two qubit experiments. The remaining task is to scale the system to many qubits while minimizing and correcting errors in the system. While this requires extremely challenging technological improvements, no fundamental roadblocks are currently foreseen.

Keywords Quantum information · Ion traps · Scalability

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1 Introduction

In 1995, Ignacio Cirac and Peter Zoller described how an ensemble of trapped ions might be used to implement quantum information processing (QIP) [1]. Several experimental groups throughout the world have pursued this basic idea, and although a useful device still does not exist, many ion-trappers are optimistic that one can eventually be built. At a modest level, the ion-trap scheme can satisfy the basic requirements for a quantum computer as outlined by DiVincenzo [2]: (1) a scalable system of well defined qubits, (2) a method to reliably initialize the quantum system, (3) long coherence times, (4) existence of gates for universal computation, and (5) an efficient measurement scheme. Most of these requirements have been demonstrated, and straightforward, albeit technically difficult, paths to solving the remaining problems exist. In this paper, we summarize primarily recent trapped-ion QIP experiments carried out at NIST, but similar work is currently being pursued at Aarhus, Barcelona, Garching (MPQ), Griffith University, Innsbruck, LANL, London (Imperial), Lucent, Ontario (McMaster), University of Michigan, MIT, NPL, Osaka University, Oxford, Sandia National Laboratory, Siegen, Simon Fraser University, Sussex, University of Ulm, and University of Washington. The Innsbruck group was represented by the talk of T. Körber at the TCP06 meeting.

2 Universal logic gates

Universal quantum computation can, in principle, be achieved by combining a series of single-qubit and two-qubit gates [3, 4]. Therefore, for experimentalists the primary goals are to provide high-fidelity one- and two-qubit gates and to implement a large number of them on a large number of ion qubits. Single-qubit gates (spin rotations) have been implemented in a number of experiments using RF or laser fields. The two-qubit gates that have been implemented so far use the Coulomb interaction between ions stored in the same trap to provide the necessary coupling between ions. Here, a single normal mode of motion acts as a data bus. The original Cirac/Zoller two-qubit gate [1] uses this principle; it has been implemented in Schmidt-Kaler et al. [5]. Several groups have also implemented single-step two-qubit gates that were proposed in Sørensen and Mølmer [6], Solano et al. [7], and Milburn et al. [8]. These gates, which can be viewed as geometric phase gates in various bases, are implemented with state-dependent optical dipole forces. They have been demonstrated experimentally in Sackett et al. [9], Haljan et al. [10], and Haljan et al. [11] (x-y basis states) and in Leibfried et al. [12] and Home et al. [13] (z basis states). The highest fidelities reported (Bell states with fidelity $F = 0.97$ were produced in Leibfried et al. [12]) are still considerably below those required for large scale "fault-tolerant" computation ($F > 0.9999$). Achieving the necessary fidelities will require substantially increased control of technical parameters such as laser intensity and ambient magnetic fields. Currently, the state of the art for number in trapped-ion QIP experiments is represented by experiments that entangle up to eight $^{40}Ca^{+}$ ions in W-states [14] and six $^{9}Be^{+}$ ions in a Schrödinger-cat-type state [15].

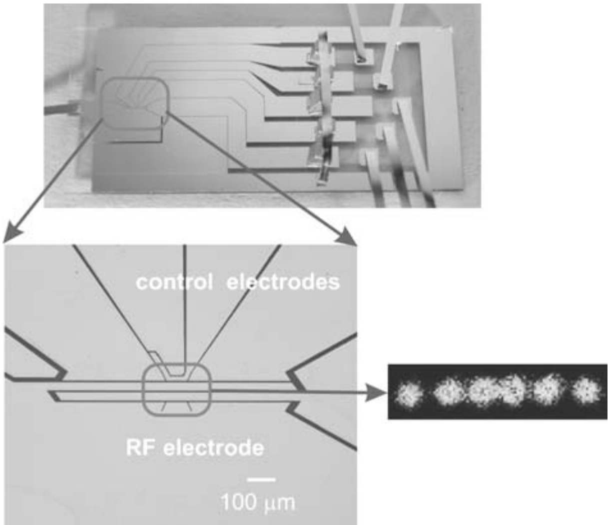

Fig. 1 Gold on fused silica surface-electrode trap. Surface electrode structures are produced by evaporating gold on a fused silica substrate (*top*). In the trap center (*bottom left*) the electrode structures are built up to 6 μm thickness by electroplating. The electrode geometry produces an harmonic trap minimum 40 μm above the surface. The *bottom right picture* shows a string of six $^{24}Mg^{+}$ ions trapped in that minimum (see also Seidelin et al. [38])

3 Scaling up with trap arrays

It is generally thought that large-scale processing time will be dominated by error correction; this will require a large number of ancilla qubits and highly parallel processing. Therefore, we desire methods to multiplex logic operations on large numbers of ions. So far, large numbers of ions can be cooled and manipulated only in single trapping zones. However, most of the practical multi-qubit gates, and all of those demonstrated so far, require addressing of individual ions and/or single motional modes. Individual ion addressing can be accomplished with focused laser beams as long as the ions aren't too close together (or equivalently, as long as the mode frequencies are not too high). This approach has been very successfully applied by the Innsbruck group. However, as the number of ions increases much beyond what is currently used, and increased gate speeds (proportional to mode frequencies) become more important, such addressing will be more difficult. In addition, mode addressing is usually accomplished by spectrally isolating the frequency of the one mode of interest. Unfortunately, when the number of trapped ions becomes large, the high spectral density of modes renders spectral isolation impractical. Therefore, many groups are considering multi-zone trap arrays where only a small number of ions are confined in the zones that are used for implementing multi-qubit gates. Sharing of quantum information throughout the array might be accomplished by moving ion qubits between zones [16, 17], by moving an information-carrying "head" ion between zones [18], by coupling separated ions with photons as an intermediary [19], or by probabilistically creating, via light coupling, entangled pairs of separated ions, which then act as a computational resource to be used later [20]. As a first step towards multiplexing using the scheme of Wineland et al. [16] and Kielpinski et al. [17], we have employed a six-zone linear array [22]. In this trap we were able to entangle ions in one zone, deliver these ions to separate zones and implement

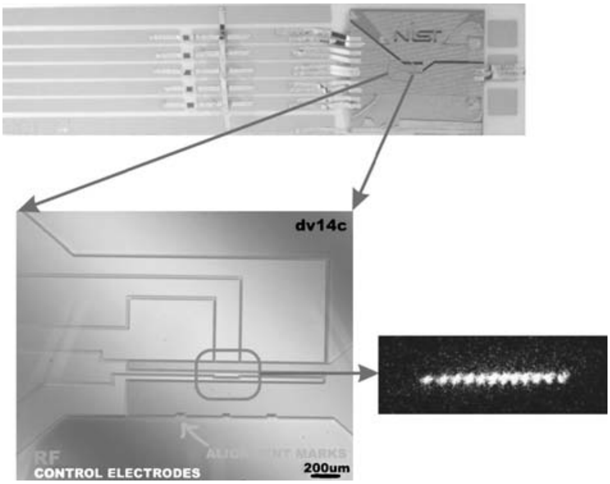

Fig. 2 Boron doped silicon surface-electrode trap. A wafer of conductive boron-doped-silicon is cut by deep reactive ion etching to produce several electrodes freely suspended over a rectangular glass frame (*top*). The electrode geometry (*bottom left*) produces an harmonic trap minimum 40 μm above the surface. The bottom right picture shows a string of twelve $^{24}Mg^{+}$ ions trapped in that minimum (see also Britton et al. [39])

further entangling gates and/or detection. Experiments that used these features included demonstrations of quantum teleportation [22], quantum error correction [23], quantum-dense coding [24], the quantum Fourier transform [25], and entangled state purification [26]. Typical trap dimensions were such that the distance from the ions to the nearest electrode was around 150 μm, and separation times were around 200 μs (for minimal heating). In the future, traps with much smaller internal dimensions should enable shorter separation times with minimal heating [23, 27]. However, with all other parameters held constant, smaller dimensions are expected to aggravate ion heating from stochastic electrode noise [28, 29]. Since the mechanism for this heating is currently not understood, many of the ion trap groups are trying to suppress it by trying different electrode materials and fabrication methods. For manipulating very large numbers of ions, two-dimensional layouts with simpler methods of construction will be required. Since (two-qubit) gate speed is proportional to the ionsÕ motional frequencies, which are in turn proportional to the inverse square of the electrode dimensions, we desire traps with dimensions smaller than those of previous traps (keeping in mind that we must simultaneously solve the heating problem). For this purpose, it should be possible to take advantage of micro-electromechanical structures (MEMS) fabrication techniques, where significantly smaller structures with better controlled material properties can be fabricated.

At NIST we constructed a two-layer trap for $^{24}Mg^{+}$ ions of the type described in [30], where the electrodes were made of commercially available boron-doped silicon, bonded with an insulating thermal-expansion-matched glass [21]. The University of Michigan group has built a monolithic two-layer trap with GaAs electrodes and AlGaAs insulators [31] and observed trapping of Cd^{+} ions [32]. A three-layer geometry that uses gold plated alumina electrodes has been implemented for Cd^{+} ions [33]. Trap geometries that would optimize the separation of ions into separate zones have been studied in Home and Steane [34]. A two-dimensional "T" junction has been demonstrated in Hensinger et al. [35]; this trap has been used to exchange the positions of two ions. A further simplification in fabrication can potentially be obtained with traps based on electrodes located in a surface [36]. These traps would be relatively easy to fabricate on a large scale and might permit on-board electronics beneath the electrode surface [37]. Surface electrode traps have been demonstrated for $^{24}Mg^{+}$ ions in a trap with gold coated fused quartz electrodes (see Fig. 1) [38] and boron-doped silicon electrodes [39] (see Fig. 2). By use of copper surface electrodes, trapping of $^{88}Sr^{+}$ ions has also been demonstrated [40]. The ion heating rate observed in Seidelin et al. [38] appears to be small enough to perform simple entangling operations. The Disruptive Technology Office has recently funded Lucent and Sandia laboratories to construct ion traps using fabrication techniques compatible with scaling up. In addition to finding a way to construct large-scale trap arrays, a way to multiplex laser beams across many trapping zones must be sought. It might be possible to use miniature steerable mirrors based on MEMS technology for this purpose. Miniature, large-solid-angle photon detectors (possibly without optics) located very near trapping zones may be essential for highly parallel detection as required in error correction.

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