

## Phase regime Josephson junction qubits

Andrew J. Berkley<sup>1</sup>, Hanhee Paik<sup>2</sup>, Huizhong Xu<sup>2</sup>, Sudeep Dutta<sup>2</sup>, J. Robert Anderson<sup>2</sup>, Christopher J. Lobb<sup>2</sup>, and Frederick C. Wellstood<sup>2</sup>

<sup>1</sup> *D-Wave Systems Inc., 320-1985 West Broadway, Vancouver BC, Canada V6J4Y3*

<sup>2</sup> *University of Maryland, College Park, MD 20742 USA*

Isolated large area Josephson junctions can be used as qubits for quantum computation [1-3]. Readout of the junction can be performed by allowing the system to tunnel to the voltage state. Single qubit gate operations are performed by capacitively coupling short microwave pulses into the junction bias current. These pulses must be carefully designed so as to achieve purely  $\sigma_x$  or  $\sigma_y$  operations. The large capacitance of the Josephson junctions, typically a few pF, allows for the use of capacitive inter-qubit coupling [4,5]. While fixed physical capacitors can be used to couple junctions, a tunable capacitance coupling scheme not only simplifies gates, but also reduces perturbation of one qubit by the tunneling of the other qubit to the voltage state. In this talk, I will discuss challenges in implementing single and two qubit gates and a tunable capacitor coupling scheme based on a Cooper pair box.

The microwave pulses for single qubit gate operations can be generated by room temperature electronics. Ideal single qubit gate pulses have a roughly Gaussian envelope and fixed phase and have durations of several nanoseconds [6]. To generate these pulses one needs full vector control of the microwave source, that is control in both amplitude and phase. Errors introduced in the pulse phase by the amplitude modulation, as typically occurs in most pulse modulators, results in single gate operations that can be described as sequenced application of  $\sigma_x$  then  $\sigma_y$  then  $\sigma_x$  on the qubit. Without proper control, this results in effectively a reduced modulation amplitude during Rabi oscillations. Also, since the microwave drive pulses are in the strong drive regime, the rotating wave approximation no longer applies [7] and the envelope of the microwave pulse must be synchronized to the microwave phase with jitter of less than 10 ps for typical qubit parameters and desired gate fidelities. Generating these desired microwave pulses is possible using state of the art electronics.

In the case of fixed capacitive coupling, two qubit operations can be performed by non-adiabatically biasing the qubits to tune the energy level spacing of one qubit into resonance with a second qubit. These bias manipulation pulses must maintain the high signal to noise ratio of the bias current while simultaneously having a high bandwidth. After manipulation, readout of one of the qubits by allowing it to tunnel to the voltage state results in a burst of current to any qubit coupled to it. I will briefly describe an experiment that measures the resulting correlated switching between the two qubits for the case of fixed capacitive coupling. This effect can be reduced by using a tunable capacitor between the qubits that can be turned off during measurement.

A tunable capacitor can be implemented by using a Cooper pair box (CPB). The capacitance of a typical CPB for this application can be tuned from 0 fF to roughly 50 fF through gate voltage control. For the simplest version of the tunable capacitor to work, one must avoid resonant interactions between the qubit and the CPB so as to keep

the CPB in the ground state. This can be achieved by designing the Josephson coupling energy  $E_j$ , of the CPB to be higher than the energy spacing of the qubit, or by only limiting the gate voltage to the regime where the CPB energy spacing is more than the qubit energy spacing. One must also keep the charging energy  $E_c$ , larger than  $E_j$  to maintain a large on/off ratio of capacitance. This tunable capacitor scheme can potentially be combined with a bus bar to allow coupling between non-nearest neighbors.

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