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A quantum computer based on recombination processes in microelectronic devices

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Abstract. In this paper a quantum computer based on the recombination processes happening in semiconductor devices is presented. A “data element” and a “computational element” are derived based on Schokley-Read-Hall statistics and they can later be used to manifest a simple and known quantum computing process. Such a paradigm is shown by the application of the proposed computer onto a well known physical system involving traps in semiconductor devices.

1. Introduction
Quantum Computers have been shown to perform certain computational tasks faster than the classical ones. As the hardware components of modern computers are being reduced in size, approaching even closer to the quantum level, quantum phenomena seem to become an apparent part of the future device design. Quantum computers are also seemed to be a necessity, if the Moore’s Law is still to be valid. Various implementation models for a Quantum Computer have been proposed [1,2]. Most of them take the representation of the quantum bit (or qubit) to be a two level quantum observable of some system, such as the spin of an electron or that of an atom nucleus. In most of them, there is a one-to-one correspondence between the quantum system and the qubit, i.e. each two level physical system corresponds to a single qubit. However new techniques have been proposed, such as Nuclear Magnetic Resonance (NMR) in which the single qubit is represented by an averaging process over a collection of two level systems [1].

In this paper, a new implementation idea is being presented involving the representation of the qubit with respect to the possible states that recombination centers in a semiconductor may exist [3,4]. The basic formalization is presented together with the basic mechanism of interaction between two distinct qubits. Since there is no way to measure the state of a single trap, the measuring process has to be an averaging one, with reference to a macroscopic property of the system. Such an idea on the implementation of such a measurement is also presented.

2. The general quantum computer
The main component of a quantum computer is the qubit, or equivalently, the system possessing a Boolean Observable. The notation for the qubits uses the following code: Labeling the eigenstates
corresponding to each observable as $|0\rangle$ for the eigenvalue 0 and $|1\rangle$ for the eigenvalue 1, we have for the general state of the qubit:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

(1)

with probabilities for obtaining via a measurement the result 0 (1) equal to $|\alpha|^2$ ($|\beta|^2$).

For a system to be able to perform quantum computations, four criteria must be accomplished [1].

- A valid qubit representation involving Observables of the system obeying (1) should be defined.
- A way in which the system can be prepared in an initial and well known state should be provided.
- A way in which the final state of the system, after the computation has halted can be measured should also exist and,
- A mechanism in which two qubits can interact and a single qubit to change its phase must be described.

Moreover, in order to describe a quantum computer, implementation of a universal quantum computing machine is needed [1]. One gate that can be provided for this task, is the CNOT gate which is the quantum analog of the XOR gate [1]. The CNOT has a control qubit and a target qubit which changes its state depending on the state of the control qubit. The mechanism of a CNOT gate working under the proposed mechanism is given in this paper.

3. The qubit representation

For two qubits to interact, a controlling mechanism must exist, in a way that the behavior of a single qubit can be controlled by another qubit. In this model this means that two qubits must obey the Pauli Exclusion Principle, so they cannot “merge” into a single state i.e. the qubits have to be fermions. Considering a single trap, statistical mechanics predict that the probability of the trap being occupied is given by [3]:

$$f(E) = \frac{1}{1 + e^{(E_F - E)/kT}}$$

where $E$ is the energy of the trap, $E_F$ is the Fermi level and $T$ is the temperature. Although the qubit could be defined in terms of a single trap being occupied or not, a different approach is being followed instead. A well defined computational basis of four is chosen, spanned by the quantum states of the composite system containing two adjacent traps, with energy levels $E_1$ and $E_2$ where $E_1 < E_2$. The correspondence between the computational basis and the physical states is such, that states of the form $|1\alpha\rangle$ are mapped to physical states containing exactly one electron, whereas those of the form $|0\alpha\rangle$ to states having the same number of electrons. This is demonstrated in the figure 1, where the black circles indicate that the trap is occupied by an electron and the white ones that a hole exists.

![Figure 1. Physical states and computational basis correspondence.](image1)

![Figure 2. Energy gaps between levels.](image2)
For any computation to take place, a known initial state for the system must be fixed. This can be achieved by forcing current injection into the semiconductor via some method, i.e. illumination. The vast majority of the qubits of a single trap level should all have the same initial value, and there must be a sufficiently large gap between energy levels, so that the distribution of qubits is uniform per trap level. The energy gaps between levels can be controlled by introducing impurities in the semiconductor material. This is shown in figure 2, where $E_2 - E_1$ is fairly large.

The general scheme is that a trap representing a single qubit can interact with the trap of the immediately lower energy. The general function of the CNOT is to flip the value of the target qubit when the control qubit is in the $|1\rangle$ state and leave the target qubit unaffected if otherwise. The complete description of the CNOT gate is given in the notation shown in figure 3a. In the general case, when the initial state is in a superposition of basis states, the operation can be expressed as a sum of operations acting on the basis states by using linearity and a general scheme for the CNOT is given in figure 3b, where $t$ stands for labeling the target qubit and $c$ the control qubit.

\[
\begin{align*}
|00\rangle & \rightarrow |00\rangle \\
|01\rangle & \rightarrow |01\rangle \\
|10\rangle & \rightarrow |11\rangle \\
|11\rangle & \rightarrow |10\rangle
\end{align*}
\]

\[
|t\rangle \quad \text{CNOT} \quad |c\rangle \\
|t \oplus c\rangle
\]

**Figure 3.** a) the CNOT notation and b) the CNOT representation via a gate scheme

In the physical model presented in this paper the CNOT operation is being executed by a signal performing the action of “electron-swap” between two adjacent traps. Such signals have been studied in quantum electronics and can be achieved physically [4,5]. The result of such a signal is to leave the state of the two traps unaltered, when they have the same number of electrons and to flip the electron otherwise. The diagrams given in figure 4 prove that this is equivalent to the generic CNOT operation. This operation is coherent since once the semiconductor is illuminated, the only interactions taking place are those between electrons in adjacent traps.

In order to measure the final state of the system a macroscopic quantity related to the trap may be measured. One such quantity could be the conductance or alternatively a DLTS signal applied on well known trapping systems such as the DX center in a GaAs diode. Such a measurement will give an average result of the number of qubits being equal i.e. to $|1\rangle$. Since the order of each individual qubit is of importance it is essential to keep track of the value for each specific qubit. This can be accomplished by introducing periodical impurities on the semiconductor and then averaging over a certain impurity region and taking the Boolean outcome as the value of the qubit corresponding to this specific region.

4. Conclusions and future work

A new idea for the development of a quantum computer architecture using Shockley – Read – Hall Recombination Statistics has been presented together with some basic ideas on how to represent the qubit and CNOT formulation in this physical model. The advantage of this technique, where it to be implemented, is that we can make quantum computation feasible using the existing semiconductor technologies.
Future work involves the formulation of the other two operations needed for universal quantum computation, namely the PHASE and Hadamard operations. A complete analysis to obtain estimations of a diagonal to the computational basis Hamiltonian is also being carried out.

![Diagram](image)

**Figure 4.** The CNOT procedure and its proof during electron-swap in our model.

5. References

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