MATERIALS AND DEVICES FOR SPIN-QUBIT QUANTUM COMPUTERS

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Abstract: The aim of the paper is elaboration of the concept for obtaining spintronic and spinqubit nanostructures applicable in quantum computing and quantum information technologies.

The convergence between the properties of quantum materials and prototype quantum devices is especially apparent in the field of 2D materials, which offer a broad range of properties, high flexibility in fabrication pathways and the ability to form artificial states of quantum matter. Along with the quantum properties and the potential of 2D materials as solid-state platforms for quantum-dot qubits, single-photon emitters, superconducting qubits and topological quantum computing elements, it is necessary to select the best methods of their preparation. 2D thin films, promising for spintronic applications, are mainly prepared by annealing of the stacks with layers of separate materials (metals, semimetals, semiconductors) received by traditional and reactive magnetron sputtering and novel laser plasma deposition techniques.

Today, usage of electron spins as quantum bits for quantum information processing in the so called quantum computers, where a qubit exists in more than one state simultaneously (until its state is measured}, is clear. Qubits in this state display a degree of correlations impossible in classical physics. This phenomenon is called entanglement and is a crucial property of quantum computing. It is also possible to create qubits from the "up" or "down" spin-states of electrons in quantum dots. But they lack the ability to control the state of a single electron well enough to perform calculations using them.

The main requirements of quantum computation are: Scalable physical systems with well characterized qubits (Zeeman Splitting); Long decoherence time; Existence of qubits at the ground state; Set of quantum gates; measurement capabilities, etc. A candidate for a qubit needs longer decoherence time than gate operation time [1]. The relevant candidates to be a qubit in quantum computing are leptons – elementary particles with spin-1⁄2, playing an important role in the Standard Model. The spin-statistics theorem implies that they are fermions and thus they are subject to the Pauli Exclusion Principle: No two leptons of the same species can be in the same state at the same time. Furthermore, it means that a lepton can have only two possible spin states namely up or down. The charged lepton is the electron; the next lepton to be observed was the muon, which was classified as a meson at the time. After investigation, it was realized that the muon did not have the expected properties of a meson, but rather behaved like an electron, only with higher mass. Another lepton - the first neutrino, the electron neutrino, was proposed in order to explain certain characteristics of beta decay.

The muon and the tau neutrinos were discovered later, up to the end of the 20th century.

According to the known properties of neutrinos, each neutrino flavor state is a linear combination of the three discrete mass eigenstates, the flavor eigenstates (creation and annihilation combinations) are not the same as the neutrino mass eigenstates and they are in associated specific quantum superposition of all three mass eigenstates it is possible to consider this family also as a good candidate to be the a qubit for quantum information systems [2].

The challenge here is to develop novel quantum circuits and qubits with better performance compared with the state-of-the-art competitors. Such components are key units for implementation of reliable practical quantum computers and quantum simulators. Success in this direction will result in a qualitatively new level of processing the quantum information using novel electronic circuits. Ultimately, our research addresses new paradigms of quantum computation for the benefit of digital economy and modern society.

Spintronics is a rapidly developing field that allows insight into fundamental spin-dependent physical properties and the development of practical applications, such as the read head sensors for hard drives in computers [3]. Recently, the so-called superconducting spintronics, which involves structures formed by ferromagnetic (FM) and superconducting (SC) layers, has emerged, promising advances in the fundamental understanding of the competition between superconducting and magnetic ordering, as well as new device functionalities. The most conventional spintronic element consists of two ferromagnetic layers coupled by a spacing layer. Its electrical resistance depends on the relative alignment of the magnetization directions of the two ferromagnets. This can be modified either by applying external magnetic fields or by injecting spin-polarized electrons.

For the progress in the field of high–performance computing and artificial intelligence, it is necessary to improve the energy efficiency and density of integration of existing circuits, which can be realized only with the superconducting (SC) electronics, mainly based on new elements - superconducting neurons and synapses. The proposed study is relevant due to the possibility of developing new energy-efficient computers with non-von Neumann architecture based on elements of superconducting spintronics. Indeed, the best modern systems on specialized semiconductor microprocessors simulate the work of about 1 million neurons and a quarter of a billion synapses. However, the largest and the most ambitious projects declare the goal of 1010 neurons and 1014 synapses. The key problem on the way to such goals is the reduction of energy release in all active elements of neuromorphic computing systems. For this reason, the use of superconducting materials seems to be the most promising direction for meeting these tasks [4].

Energy efficient memory has been the main detractor for multiple superconducting digital properties. Recently, fundamental research in superconductor-ferromagnet thin-film tunnel structures created a new opportunity
to solve this long-standing problem. Superconductivity and ferromagnetism, two deeply antagonistic electronic properties, can co-exist in the form of Magnetic Josephson Junctions (MJJs) [5].

The interplay between superconductivity and ferromagnetism in artificial multi-layer hybrid systems is very promising for the application in superconducting electronics, spintronics and magnonics. In the last decade various areas of the so-called alternative or post-silicon electronics have been actively developed. The search for alternatives to silicon electronics is associated with the impossibility of a further fundamental increase in the integration of semiconductor elements due to the manifestation of quantum phenomena that disrupt the normal functioning of integrated circuits, as well as the impossibility of efficient heat dissipation in the circuit elements.

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