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Epitaxial thin-film $Pd_{1-x}Fe_x$ alloy: a tunable ferromagnet for superconducting spintronics

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ABSTRACT **Thin epitaxial films of the palladium-rich $Pd_{1-x}Fe_x$ alloy were synthesized and extensively studied as a tunable ferromagnetic material for superconducting spintronics. The (001)-oriented MgO single-crystal substrate and the composition range of $x = 0.01$–0.07 were chosen to support the epitaxial growth and provide the films with magnetic properties spanning from very soft ferromagnet for memory applications to intermediately soft and moderately hard for the programmable logic and circuit biasing, respectively. Dependences of the saturation magnetization, Curie temperature and three magnetic anisotropy constants on the iron content x were obtained for the first time from the analyses of the magnetometry and ferromagnetic resonance data. The experimental results were discussed based on existing theories of dilute ferromagnetic alloys. Simulation of the hysteresis loops within the Stoner-Wohlfarth model indicates the predominant coherent magnetic moment rotation at cryogenic temperatures. The obtained results were compiled in a database of magnetic properties of a palladium-iron alloy in a single-crystal thin-film form considered as a material for superconducting spintronics.**

Keywords: palladium-iron alloy, thin epitaxial films, magnetization, magnetic anisotropy, superconducting spintronics

INTRODUCTION

Conventional complementary metal–oxide–semiconductor (CMOS)-based electronics is already approaching its physical limits [1–5], so the end of conventional Moore's law scaling [6] is really near. Approaches beyond the Moore suggest various solutions comprising new materials and devices, more efficient architectures and packaging, and new models of calculations [4,5]. One of them pushes forward heterogeneous multi-chip architectures/packages where every kind of calculations is performed by a specialized processor based on optimal device physics.

Forefront in the high-end supercomputing is associated with superconducting Josephson-junction technology [7–10], which offers up to two orders increase in the clock frequency (100 GHz and beyond) and six orders reduction in the energy dissipation per bit operation—incredible gain against present semiconductor processors [11,12]. Requirement of the cryogenic cooling may seem complicated; however, it should not be a scare, thanks to the development of close-cycle refrigeration. The superconducting single flux quantum (SFQ) Josephson logic technology [13] was implemented in the US Cryogenic Computing Complexity (C3) Program [14,15], aiming to demonstrate a route towards the supercomputing system with the total performance of up to 1000 PFLOPS utilizing sub-ns access time Josephson magnetic random access memory (MRAM) [16–18].

Josephson junctions incorporating ferromagnetic layers were proposed not only for the superconducting spintronic memory, but also for the programmable and reconfigurable digital circuits, dissipationless and reconfigurable clock and biasing networks in SFQ circuits. To realize these applications, a ferromagnetic material which is weak in small spin-polarization of the conduction band is required [19,20], providing insensitivity to the interface roughness, and the range of the layer thickness (10–30 nm) comfortable for the deposition techniques. To restrict a number of materials involved into the production technology, a tunable ferromagnet would be desired since clocking and biasing

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