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Recent Advancements in the Field of Ballistic and Non-Ballistic Spin-Based Field-Effect Transistors

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Abstract. The magnificent increase in the performance of integrated circuits is made possible by semiconductor Physics. Due to very large-scale integration, scaling has approached its fundamental limits, which is the biggest challenge for the semiconductor industry. Therefore, in the recent years researchers across the globe are focusing on emerging field of spintronics. In this thrust area of spintronics research, spin field effect transistor (s-FET) is an extensively studied device. In literature, researchers have studied and optimized two main types of spin field effect transistors namely Ballistic and Non-Ballistic spin-field effect transistors. This research paper has presented the recent developments in the field of Ballistic and Non-Ballistic spin-field effect transistors. This paper has briefly explained the approach to design, development and fabrication of s-FET by taking a case study. Firstly, the spin field effect transistor was proposed by Datta–Das, which has proved to be the milestone in the area of spintronic technology. Mainly, spin transistor is prepared using a ballistic semiconductor, sandwiched between ferromagnetic metallic source and drain contacts.

INTRODUCTION

In recent years, the functionality of data processing and information processing has improved due to spintronics by overcoming the serious limitations of conventional electronics. In this development, spin field effect transistor (s-FET) is the most studied device which is typically composed of a lateral semiconducting channel with two ferromagnetic contacts. s-FET is foundation of spintronics progress [1]. s-FET is working on the basic principle of modulation of resistance with control on the spin of the carriers by employing ferromagnetic contacts. Ferromagnetic contacts act as generator and detector of polarization [2]. In s-FET, spin transport is controlled through the gate voltage. The operation of spin transport phenomenon at nanoscale is useful for building spin-based quantum bits for processing quantum information [3].

During literature survey, it is observed that Datta-Das has firstly proposed s-FET which is applicable to non-ballistic semiconductor channel of two-dimensional electron gas (2DEG) system. But many researchers have studied s-FET with ballistic regime of 2DEG system. The present research paper in its brief review has tried to summarize the recent developments in

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s-FET under two main categories that is ballistic and nonballistic type s-FET. The present manuscript is divided into three main sections, namely Ballistic s-FET, non-ballistic s-FET and challenges & future outlook associated with s-FET.

BALLISTIC s-FET

The ballistic s-FET is a rapidly growing side of spin transistors. In this section, the brief overview about the recent development in ballistic s-FET is summarized. The meaning of ballistic transport in the present work is to maintain spin direction in channel, without any scatterings. In other words, during the movement of electron from source to drain, the minimum number of scattering centers should come across the path. If the spin transport is affected by the presence of more scattering centers in the channel, it comes under the category of nonballistic s-FET.

Koo et al investigated the high mobility in s-FET based on InAsheterostructure. This also demonstrated the electrical injection and detection of ballistic spin-polarized electrons in s-FET. Further, it is observed that conduction of s-FET is a function of applied gate voltage [4]. Xiao et al studied the Ballistic transport in s-FET by focusing on the phenomenon such as, spin–orbit coupling, interfacial scattering and the different internal exchange energies for the ferromagnet regions. Griffith boundary conditions are used to analyze the transmission coefficients. The study concludes that transmission probability and conductance oscillation of the s-FET depend on device size, interfacial barriers and mainly on spin–orbit coupling precession [5]. Osintsev et al studied the properties of silicon Ballistic spin fin-based field-effect transistors using two ferromagnetic contacts having spin polarization $0 < P < 1$. The results of the study show that [100] and [110] orientated structures strongly influence to the conductance [6]. Osintsev et al investigated the transport properties of sFET at room temperature as a function of strength of the spin-orbit interaction using Schottky barriers created between the contacts and the channel. This concludes that silicon fins of the [100] orientation have the best performance and it is suitable for practical application of sFET [7]. Figure 1 shows the architecture of s-FET used by Osintsev et al.

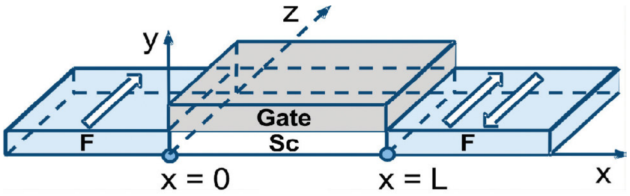

FIGURE 1. Architecture of sFET (Osintsev et al, 2013)

Gao et al demonstrated simulation of s-FET by considering the factors such as spin scattering, tunneling and self-consistent charge distribution. This work results in two solid outcomes, first one is to increase the energy of spin splitting in drain, raise potential barrier to block the drain leakage current and second is to introduce the spin-selective tunneling oxide layer between source and drain [8]. The s-FET architecture used by Gao et al is shown in Figure 2.

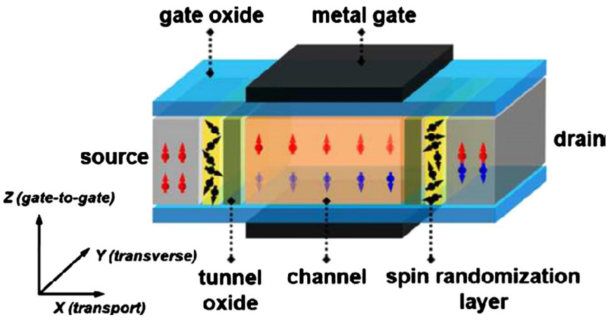

FIGURE 2. The s-FET architecture (used by Gao et al, 2010)

Jeong et al focused on the issue of multichannel effects in ballistic S-FET. The results of the study clearly show that when 2-dimentional electron gas is weakly diffusive, the fluctuation in modulation signal is observed and it depends on physical properties of sample [9]. Jiang et al studied the conductance properties in ballistic s-FET by considering Rashba effect, band mismatch, and spin polarization in ferromagnetic electrodes. This study shows that conductance of s-FET has prominent peaks for potential barriers at the contact/channel interfaces. Hence, switching action in ballistic s-FET is achieved by tuning band mismatch or direction of the magnetic field. The spin precession in channel of s-FET becomes noticeable as the spin polarization in the contacts increases [10]. Jiang et al verified the tunneling magnetoresistance properties of ballistic s-FET by considering the parameters Rashba spin–orbit coupling, presence of an in-plane magnetic field, band mismatch, and spin polarization in the ferromagnetic electrodes. Results of the present study show that as band mismatch is altered, the magnitude and sign of tunneling magnetoresistance is significantly modulated by Rashba spin–orbit coupling process. In study, it is also observed that variation in tunneling magnetoresistance is produced as a function of Rashba spin–orbit coupling strength and magnetic field [11]. Sherman et al studied the spin dynamics and relaxation in doped two-dimensional electron systems, dopants create the random fluctuations of the Rashba spin-orbit coupling. The random contribution to the spin-orbit coupling originates from random-spin precession, due to the presence of dopants. The randomness in spin precession is also important for device fabrication [12].

NON-BALLISTIC s-FET

This section deals with the non-ballistic s-FET and recent developments in it. It is observed that non-ballistic s-FET side of spin transistor is a less grown technology compared to ballistic s-FET.

Schliemann et al proposed s-FET based spin-orbit coupling of Rashba as well as the Dresselhaus types. In this work, spin transport through device is made tolerable for spin-independent scattering processes, to study s-FET in nonballistic mode. The ballistic transport s-FET proposed in this work has unique benefits of cancellation of Rashba and Dresselhaus effects, improve the performance of s-FET than ballistic s-FET [13]. Shafir et al investigated the spin polarization drag in an $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure as a function of gate voltage. The focus of study is to analyze the role of Rashba and Dresselhaus spin-orbit interaction in the nonoballistic s-FET. In this work, actual parameters of materials were used for simulation of spin dynamics as a function of gate voltage. The estimated modulation in spin polarization was found to be in the range of 15–20 %. This result shows that practical application of s-FET with this range of spin polarization is not possible. But, this issue can be resolved by optical pulse-probe technique [14]. Ohno et al applied the semiempirical Monte Carlo simulation for spin transport in Datta-Das proposal for s-FET. This study gives interesting results such as spin helix state in two-dimensional electron gas system is adequately strong against D'yakonov-Perel' spin relaxation, which makes Datta-Das-type s-FET operable in the nonballistic transport regime. Also, it is marked that switching action on s-FET is achieved by creating a 180° phase difference in the spin precession motions, which is very much necessary for practical application [15]. Xu et al apply the lattice Green's function to study s-FET in one-dimensional case. The results of the study give outstanding coherent regime, which improve inelastic scattering and lateral confinement in the control of spins [16]. During study it is concluded that non-ballistic s-FET needs more study and research reports, which explore the anonymities associated with non-ballistic s-FET.

CHALLENGES AND FUTURE OUTLOOK

Spinvalve and s-FET are very important devices in the spintronics technology. Following are major challenges for the practical application of s-FET [17, 18],

- Injection of spin-polarized flow of electron in semiconducting channel.
- Control on Rashba spin-orbit coupling in the semiconducting channel through gate voltage.
- Serious fundamental challenges like the lowspin-injection efficiency, resistance mismatch, spin relaxation and the spread of spin precession angle are still not resolved entirely.

In conventional electronics, the operations like logic, communication and storage require separate device. But semiconductor spintronics has ability to perform all these three operations within single device by exploiting the spin coherence.

CONCLUSIONS

It is concluded that the study of s-FET in ballistic and non-ballistic regime is very much necessary for the deeper understanding of s-FET. Also, to reach a rigid conclusion about selection of ballistic and nonballistic s-FET, extensive study is required, as the study of s-FET is in early stages. The realization of more spintronics devices is an interesting and challenging task. It requires advanced technology for fabrication of device. To study s-FET, a sound understanding about materials science, semiconductor Physics and conventional electronics is very much essential.

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