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Charge Properties of the MOS Transistor Structure with the Channel Made from a Two-Dimensional Crystal

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Abstract—Two-dimensional (2D) semiconductor crystals can be applied to further increase the efficiency and speed of field-effect transistors. Such transistors are free from some of the adverse effects present in the traditional MOS transistors when their size is reduced. In this study, the model of the transistor MOS structure with the channel made of a 2D-crystal is proposed and its charge properties are investigated. The numerical simulation of such characteristics is carried out within the range of variations of the electrophysical properties of 2D-crystals representative of $MoSe_2$, WS_2, WSe_2, $ZrSe_2$, $HfSe_2$, and $PtTe_2$. The self-consistent correlation between electrophysical parameters of the structure via the chemical potential is found, and the effect of the potential of the field electrode and the gate insulator's capacitance on them is demonstrated. The calculations of the steepness of the transfer characteristic and the voltage gain of such a transistor structure demonstrate that, for the channel made from transition metal dichalcogenides (TMD) with the forbidden gap band falling in the range 0.25–2.1 eV, the magnitudes of these parameters can attain 0.1 mA/V and 1000, respectively.

Keywords: two-dimensional (2D) crystal, transistor structure, quantum capacitance, transfer characteristic, steepness, voltage gain

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INTRODUCTION

The application of two-dimensional (2D) semiconductor crystals can solve the problem of further increasing the efficiency and speed of field-effect transistors. Such transistors are free from some of the adverse effects present in the traditional MOS transistors when their size is reduced. The 2D-crystals of transition metal dichalcogenides (TMD) MeX_2 that are one or several monomolecular layers thick, where *Me* is Mo, W; *X*—S, Se, and Te, are of principal practical interest [1–4]. These materials, depending on their composition and thickness, have the band gap of 1 to 2 eV and electron mobility of 60 to 500 $cm^2/(V\,s)$. Using the TMD as the channel of the MOS transistor ensures the efficient operation of such devices in the microwave range and under elevated temperatures [5–10]. In addition, the direct band gap transition in the TMD crystals that have a monomolecular thickness determines the potential of their application in integrated optoelectronics [11–14].

The existing technology provides an opportunity to form 2D-crystals of TMD on the substrates traditional for microelectronics and to form MOS transistor structures on them. Apart from the undeniable advantages of using 2D-crystals in solid-state electronics, the description of charge effects in the MOS transistors manufactured based on them and adequate modeling of the electrical characteristics of such transistors continue to be relevant.

The aim of this work is to find the correlation of the electrophysical properties of the channel of a 2D-crystal in the MOS transistor configuration with its charge parameters and simulate the electric transfer and output characteristics of such a configuration taking the revealed regularities into account.

THE MODEL OF MOS STRUCTURE WITH THE CHANNEL OF 2D-CRYSTAL

The object of consideration is a MOS transistor structure, including the source, the 2D-crystal as the channel, the field gate isolated by the oxide dielectric, and the drain (Fig. 1), arranged on a flat substrate. The field effect enabling us to control the flowing current as the result of varying the voltage of the field electrode, in a similar way to traditional MOS structures, is the base of operation of a transistor with a 2D-crystal. In terms of its construction, the MOS transistor with a 2D-crystal is closer to the traditional internal-channel MOS transistor; however, it is distinguished by the absence of a semiconductor substrate. For this reason, its channel cannot exchange charge carriers with other structural elements of the transistor. The conductance of the 2D-channel is controlled exclusively by varying the chemical potential of the charge carriers. The dif-