Microwave Detection Using 2-Atom-Thick Heterojunction Diodes

Martino Aldrigo¹, Mircea Dragoman¹, Sergiu Iordanescu¹, Dan Vasilache¹, Adrian Dinescu¹,
Giorgio Biagetti⁵, Luca Pierantoni⁵, Davide Mencarelli⁵

¹IMT-Bucharest, Voluntari (Ilfov), Romania
⁵Università Politecnica delle Marche, Ancona, Italy

Istituto Nazionale di Fisica Nucleare, Frascati (Roma), Italy
1martino.aldrigo@imt.ro

Abstract—In this paper, a two-dimensional material-based diode for microwave detection at 2.49 GHz with photodetector capabilities is presented. The diode consists of a molybdenum disulphide monolayer/graphene monolayer heterojunction transferred onto a silicon/silicon dioxide substrate, and patterned by means of nanolithography techniques to obtain a geometrical self-switching diode. The interaction between the two monolayers gives rise to a double-stage device, which behaves as a back-to-back diode in the [-3, +3] V range, and as a tunnel diode when exceeding +10 V. The heterojunction can be reproduced on large scale due to its CMOS compatibility; it does not need any particular doping process thanks to its geometrical nature and can be used efficiently as microwave detector up to 10 GHz, with the best performance around the ISM 2.45 GHz band. Last, a rigorous equivalent circuit model based on the Foster’s method is provided, which relies on the measured scattering parameters at high frequencies. This way, the device can be exploited in circuit-based numerical tools for the design of complex microwave front-ends.

Keywords—microwave devices, photodetectors, molybdenum disulphide, graphene, heterojunctions.

I. INTRODUCTION

Microwave detectors are very well-known components used in wireless communications. They rely essentially on a diode or a transistor that are able to sense the presence of the incoming microwave radiation, the level of sensitivity (i.e., minimum power detected) depending on the device itself. The literature published in this domain is so vast that it is practically impossible to give a comprehensive list of references. However, in the last years the attention has been moving towards geometrical diodes [1], i.e., diodes which are created by etching channels in a planar semiconductor/semimetal. These devices are called “self-switching diodes” (SSD), which have been demonstrated to detect both microwave [2],[3] and THz [4] signals. An SSD is different from classical diodes, in the sense that no junctions are necessary (hence no doping), and its physics relies upon a nonlinear current, which flows through nanometer-sized parallel channels and is controlled by field-effect phenomena. In principle, an SSD could be modelled as a 2D field-effect transistor (FET), with short-circuited gate and drain. This type of devices has been fabricated using various semiconductor and 2D electron gas (2DEG)-like materials, like AlGaN/GaN [5], InAs, graphene and molybdenum disulphide (MoS₂). Nevertheless, to the authors’ knowledge no attempt has been made so far to fabricate an SSD based on a monolayer MoS₂/monolayer graphene heterojunction (HJ), mostly due to (i) the difficulties in the growth of MoS₂ at the wafer level and (ii) its low mobility. In this respect, this paper aims at overcoming this technological gap by presenting a MoS₂/graphene SSD on high-resistivity silicon/silicon dioxide (HRSi/SiO₂) substrate. In the following Section II, the motivation will be shown, together with the design and fabrication of the diodes. Then, in Section III the DC and microwave characterization of the diodes will be provided. Finally, in Section IV a rigorous circuit model will be described, which uses the measured scattering parameters to create a high-frequency equivalent circuit, suitable for its exploitation in numerical tools for the design of complex front-ends.

II. MOTIVATION, DESIGN AND FABRICATION OF THE HETEROJUNCTION-BASED SSDS

A. Motivation

As stated before, MoS₂ is harsh to be grown at the wafer level and possesses a low mobility with respect to other semiconductors (but now comparable with that of silicon). In spite of these limitations, MoS₂ has interesting properties: it is the most studied atomically-thin material after graphene; MoS₂ monolayer is a direct bandgap semiconductor, with a bandgap of about 1.9 eV, which decreases as the number of monolayers increases (its bulk counterpart being an indirect semiconductor with a bandgap of about 1.2 eV). On the other side, graphene (“the silicon of the 21st century”) is a zero-gap semimetal with high room-temperature mobility (in the order of 1000’s cm²/V·s), which can be used for detection/rectification of microwaves up to THz if properly patterned at the nanoscale. Hence, the combination of these two 2D materials in their monolayer form could benefit from their individual advantages, creating a new type of device with unmet properties.

B. Design

The design considered here for the SSDs is, as said before, a 2D FET with short-circuited gate and drain, and narrow channels in parallel. A peculiar aspect of the SSD design is that four different channel widths \( W_{ch} \) are envisaged: 30 nm, 50 nm, 75 nm and 100 nm. In Fig. 1, a top-view and (red inset) cross-
section of the diode structure can be seen on the left, whereas on the right the general scheme of the single channel with the main dimensions is displayed ($W_{ch} = W_0 = 30, 50, 75, 100\,\text{nm}$, and $L_{ch} = 1.1\,\mu\text{m}$). Such a diode can be modelled as a capacitive divider formed by a quantum capacitance $C_Q$ and a substrate capacitance $C_S$ [6], connected in series. Each channel is capacitively coupled to the drain voltage through $C_D$ and $C_S$. In general, the Sichman-Hodges model can be used for the $I-V$ characteristic of such devices:

$$I = N\mu C_Q \frac{W_{ch}}{L_{ch}} V^2$$  \hspace{1cm} (1)

where $N$ is the number of channels in parallel and $\mu$ is 2D material’s mobility. In the present work, the total number of channels in parallel is 12 or, in other words, the diode can be modelled as 12 voltage-controlled current generators in parallel.

$$I = N\mu C_Q \frac{W_{ch}}{L_{ch}} V^2$$  \hspace{1cm} (1)

III. DC AND MICROWAVE CHARACTERIZATION OF THE HETEROJUNCTION-BASED SSDS

A. DC Measurements

The DC measurements were performed using a Keithley SCS 4200 characterization system, connected to a SÜSS MicroTec measuring platform. Of the 16 fabricated structures, 13 (81%) presented no exfoliation issues of the Au layer. The HJ-based diodes with the highest DC current $I_{DC}$ are the ones with $W_{ch} = 75\,\text{nm}$, followed by $W_{ch} = 100, 50$ and 30 nm (the difference between 75 nm and 100 nm in the $I_{DC}$ values being 13%). Nevertheless, a very interesting characteristic is the high breakdown voltage, much higher than that measured for any other SSD fabricated so far. In Fig. 3 one can notice the following: first, in the DC voltage ($V_{DC}$) range $[-3, 3]\,\text{V}$, the HJ behaves like a slightly asymmetric “back-to-back” diode (Fig. 3a, “dark” curve), thanks to the semiconducting nature of the MoS$_2$ monolayer and to the double metallic-HJ contact; $I_{DC}$ attains values between ~300 nA and 300 nA. Second, since MoS$_2$ is a light- and IR-sensitive semiconductor, the application of a white light source of variable intensity allows increasing $I_{DC}$ of 2.6× times (Fig. 3a, “light” curves). Third, at $+10\,\text{V}$ the SSD behaves as a tunnel diode (Fig. 3b), with an abrupt increase of $I_{DC}$ up to 100’s $\mu\text{A}$ (hence of a factor 10$^3$). This means that the breakdown voltage is much higher than ±6–7 V as in the case of pure graphene-based SSDs. This phenomenon could be explained by the combination of the MoS$_2$ bandgap with the charge trapping at the MoS$_2$/graphene interface; hence, the energy necessary to release these charges is associated to a high value of $V_{BDC}$. Moreover, repeated measurements spanning between -20 V and +20 V do not cause any degradation of SSDs’ performance, meaning that the proposed HJs could be used in power electronics, which can require up to tens of Volts.

![Fig. 1.](image)

C. Fabrication

In Figs. 2a and 2b two optical pictures of the fabricated HJ-based SSDs are shown, while Fig. 2c is a SEM picture offering a magnified view of the diode.

![Fig. 2.](image)

For the fabrication of the HJ-based SSDs, some customized samples were purchased from 2D Semiconductors (Scottsdale, AZ, USA), namely 1×1 cm$^2$ 2D HJs made of SiO$_2$/Si (SiO$_2$ thickness of 90 nm, and HRSi wafer with thickness of ~500 μm, resistivity of ~10,000 Ω·cm), monolayer MoS$_2$ (on SiO$_2$/Si), and monolayer graphene (on MoS$_2$). The fabrication involved four big steps: 1) deposition of metal pads by a lift-off process, in order to define diodes’ areas and to improve the layers’ adhesion to the SiO$_2$/Si substrate; 2) diodes’ patterning using an electron-beam lithography (EBL) process and manufacturing by dry etching; 3) to avoid any damage to the HJ, the diodes were covered by a negative electronresist (hydrogen silsesquioxane–HSQ); 4) manufacturing of the coplanar waveguide (CPW) lines (for on-wafer measurements) by a lift-off process.

![Fig. 3.](image)

B. Microwave Measurements

The HJ-based SSDs were measured at high frequencies by using a microwave generator (Agilent E8257D) to transmit an AM carrier frequency between 900 MHz and 10 GHz. The input power was varied between -1 dBm and +10 dBm. The frequency of the rectangular-shape modulating signal was set to 1 kHz. The output of the diode was registered by a digital oscilloscope (Tektronix SR560) connected to a load resistance of 1 MΩ. A DC external source (Agilent E3631A) was deployed to bias the diode (in the range [0, +1]\,\text{V}) through a bias tee. In Fig. 4 it is shown the detected DC voltage $V_{DET}$ at 2.49 GHz, for an input power of +10 dBm and a bias of 0 V.
$\v$ is about 10 mV (and about 65 mV with bias of +1 V). This is
the best result obtained so far, since at higher frequencies $V_{\text{DET}}$
dergoes distortion phenomena. When measuring the
scattering parameters of the SSD with a VNA (Vector Network
Analyzer, Anritsu 37397D), one can extract a rough frequency-
dependent parallel $R_{\text{eq}}C_{\text{eq}}$ equivalent circuit in the band 0.1–
4 GHz. In this case, $R_{\text{eq}}$ attains the values 680 $\Omega$ (at 0.1 GHz)–
18 $\Omega$ (at 4 GHz), whereas $C_{\text{eq}}$ spans the range 11 pF (at
0.1 GHz)–0.14 pF (at 4 GHz). Hence, a matching circuit is
necessary for optimal power transfer to the SSD.

Step 2: fit a rational function to the each distinct element
using Matlab’s invfreqs function. That ensures that all poles
have a non-positive real part and yields an approximation
without artifacts, and it must be $|\v \v |-1$.

Step 3: expand $Y(s)$ as $Y(s) = k_1 s^2 + k_0 + \sum_{i=1}^{N_R} r_i \left( s - p_i \right)$
where $r_i \in \mathbb{C}$ and $p_i \in \mathbb{C}$ are the poles and residues,
respectively. Since the coefficients $a_i$ and $b_i$ are real, they are
either real or in complex conjugate pairs. Let $N_R$ and $N_C$ be the
number of real poles and conjugate pairs, respectively. $Y(s)$
can be written, after proper reordering of the above pairs, as

$$Y(s) = k_1 s^2 + k_0 + \sum_{i=1}^{N_R} \frac{r_i}{s - p_i} + 2 \sum_{i=1}^{N_R+N_C} \frac{R_r(s)-R_{r1}(s)}{s^2 - 2(p_r(s)+p_r1(s) \cdot 2}.$$  

Step 4: synthesize the electrical network. The first three terms are
trivial: $k_1$ is a capacitance, $k_0$ is a resistor, and simple poles
correspond to series LR circuits. Quadratic terms can be
matched to LC resonators with a resistance in series with the
inductance and a conductance in parallel to the capacitance.

Step 5: denormalize the dimensionless quantities just computed
to get real circuit element values, using the denormalization
factors $R_0 = Z_0, L_0 = Z_0/2\pi f_0, G_0 = 1/Z_0, C_0 = 1/2\pi f_0 Z_0.$
Applying the above theory, we get the equivalent circuit shown
in Fig. 5, which includes also negative components, and the
Corresponding fitting to the experimental data (Fig. 6). It is
known that diodes with variable capacitor and tunnel diodes (as
in the present work) have led to include also negative resistors
(besides lumped passive elements) as circuit components in
the analysis and synthesis of linear networks [7]. Thus, it is possible
to represent any linear $n$-port circuit in terms of real and
physically realizable rational functions.

Fig. 5. Synthesized equivalent circuit of the HJ-based SSD. μ-network: $R_1$
= 171.68 $\Omega$, $L_1 = 304.39$ pH, $R_2 = -585.59$ $\Omega$, $L_2 = -85.58$ nH, $R_3 = 6.25$ $\Omega$, $L_3 = -5.24$ pH, $R_4 = -279.44$ $\Omega$, $L_4 = -1.51$ nH, $G_1 = -1.69$ mS, $C_1 = -85.70$ fF, $R_5
= -16.61$ $\Omega$, $L_5 = -1.19$ $\mu$H, $G_2 = -190.36$ aF, $C_2 = -3.07$ mS, $C_3$
= 2.09 ff, π-network: $R_1 = -18.49$ $\Omega$, $L_1 = -59.82$ pH, $R_2 = 12.36$ $\Omega$, $L_2 = 86.37$
\pH, $R_3 = -70.76$ $\Omega$, $L_3 = -5.11$ nH, $R_4 = -21.62$ $\Omega$, $L_4 = -4.89$ nH, $G_3$
= 34.80 mS, $C_3 = -1.14$ nF.

Fig. 6. Fitted (equivalent circuit) vs. measured (a) $S_{11}$ and (b) $S_{12}$.

V. CONCLUSION

In this paper, we have presented the design, fabrication,
DC/microwave characterisation and circuit modelling of a self-
switching diode based on a MoS$_2$/graphene heterojunction.
The experimental results prove that two-dimensional materials can
be integrated profitably into modern and future electronics. In
this respect, the equivalent circuit is a powerful tool to model
such devices in a standard circuit simulation.

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