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Capacitance-voltage characterization of BP layers grown by PECVD mode

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Abstract. Boron phosphide is perspective material for solar cells based on BP/n-Si selective heterojunction. Here, BP layers grown by plasma-enhanced chemical vapor deposition at low temperature in continuous mode with flows of diborane and phosphine. It was shown rectifying behavior of current-voltage characteristics in Au/BP/n-Si structure with increasing of plasma power and additional dilution of gas mixture by hydrogen flow due to improvement of conductivity, and Au/BP/p-Si heterojunction showed photoelectric response. In result, BP layers are donor doped, and capacitance-voltage profiling at different temperature prove temperature activation of conductivity in BP.

Keywords: heterojunction, selective contact, boron phosphide, capacitance-voltage profiling

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Вольт-фарадные характеристики слоев BP, выращенных методом PECVD

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Аннотация. Фосфид бора является перспективным соединением для создания солнечных элементов на основе гетероперехода BP/n-Si. В данной статье были исследованы свойства слоев BP, выращенных методом низкотемпературного плазмохимического осаждения из газовой фазы, в режиме непрерывного осаждения с потоками диборана и фосфина. Было продемонстрировано выпрямляющее поведение структуры Au/BP/n-Si при увеличении мощности плазмы, а также разбавления дополнительным потоком водорода, что привело к увеличению проводимости, а структуры типа Au/BP/p-Si показали фотоэлектрический отклик при освещении солнечным спектром. В результате полученные слои являются донорно легированными, а измерения профилей концентрации свободных носителей заряда, полученные из вольт-фарадных характеристик при разных температурах, подтверждают активацию проводимости слоя BP.

Ключевые слова: гетеропереход, селективные контакты, фосфид бора, вольт-фарадная характеристика

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Introduction

Nowadays, silicon technology is the most advanced in terrestrial photovoltaic so the use of silicon substrates will remain an important condition for the implementation of a highly efficient solar cell for mass production. One of the methods for creating single-junction solar cells is the formation of selective contacts to silicon substrate. The materials widely used to make such contacts to crystalline silicon are transition metal oxides and amorphous or microcrystalline silicon [1]. Despite being well-developed technologically the usage of these materials has significant disadvantages such as parasitic absorption in short-wavelength region and high temperature instability in further production stages [2].

Consequently, it is perspective to investigate of the alternative semiconductor materials namely binary A3B5 phosphide compounds. For example, it was theoretically shown in [3] that boron phosphide is one of the most promising compounds for the creation of p-type TCM (transparent conducting material) to n-Si substrates, since it has an indirect band gap with a large difference between the energies of the direct (4 eV) and indirect transitions (2 eV), which leads to a large break of the conduction band at the p-BP/n-Si heterojunction, creating a selective contact for holes. In our previous work [4], BP layers were grown by plasma-enhanced chemical vapor deposition (PECVD) in continuous mode from gas mixtures of trimethylborane (TMB) and phosphine (PH_3) used as precursors. However, high content of carbon was detected, and capacitance measurements revealed the presence of electron accumulation at the BP/Si interface, which can be explained by lowly doped or undoped BP and Fermi level pinning at the BP/Si interface due to the presence of interface defect states. In this study, we used diborane instead TMB to exclude carbon incorporation in BP layers. One more significant feature of the BP/Si interface is its valence band offset that scatters over a wide range from −0.3 to 0.9 eV, according to literature data. It could both ensure and lower the selectivity of charge carriers depending on its sign and in addition, its magnitude could affect the sensitivity to the surface states. Thus, in order to predict the efficiency of solar cells based on p-BP/n-Si, investigation of electrophysical properties of the BP/Si heterojunction grown in different conditions by capacitance-voltage and current-voltage methods were done in this study.

Materials and Methods

Boron phosphide layers were grown in a standard Oxford PlasmaLab 100 PECVD (13.56 MHz) plasma chemical deposition in continuous PECVD mode. BP layers were deposited on n-type double-sided polished c-Si substrates with a doping level of $N_d = 1\times10^{15}$ cm−3 at 350 °C, with a different plasma power of 20, 100 and 200 W and pressure of 1000 mTorr. Furthermore, additional dilution by flow of hydrogen of 100 sccm also was used in several samples. Flow ratio of precursors PH_3 and B_2H_6 was equal to 2. The detailed parameters of the deposition are shown in the Table. Then, ohmic contact was formed to rear side of silicon substrates by deposition of n-GaP (5 nm) and further evaporation of silver, and gold was thermally evaporated on BP through hard mask with circle holes ($d = 1$ mm) to formation of Schottky barrier. Current-voltage characteristics of the samples were measured at room temperature using Keithley 2400 source meter, capacitance-voltage measurements were performed at 100kHz and with test level of 50 mV in helium cryostat Janis CCS-400H/204 at wide range temperature of 12..800 K using Agilent E4980A-001 RLC meter and Lake Shore 335 temperature controller.

Table

Growth conditions of BP layers grown by continuous PECVD method

Sample	Plasma Gas	Plasma Power, W	B_2H_6, sccm	PH_3, sccm	H, sccm	Pressure, mTorr	Thickness, nm
Ox915		20	40	20	0		285
Ox916		200	40	20	0		276
Ox917	H	200	20	10	100	1000	360
Ox924		100	20	10	100		370
Ox925		20	20	10	100		235

Results and Discussion

The measured current-voltage characteristics are shown in the Figure 1. It can be seen that conductivity of layers increases with increasing of plasma power and the presence of additional flow of hydrogen in chamber. Moreover, clear rectifying behavior in the direct voltage bias is observed for samples Ox917 and Ox924 grown with 200 W/100 W plasma power respectively and 100 sccm of hydrogen flow: it marks the existence of space charge region at interface Au/BP due to Schottky barrier that suggests donor doped BP layer. This suggestion could be confirmed by the rectifying behavior in the direct bias voltage (after changing measurement polarity) for Ox924 sample grown on p-Si, which, in its turn, indicates p-n junction at interface BP/p-Si. Current-voltage characteristic of this sample under solar illumination reveals the presence of photovoltaic effect in heterostructures with open-circuit voltage of ~ 0.3 V.

a) *b*)

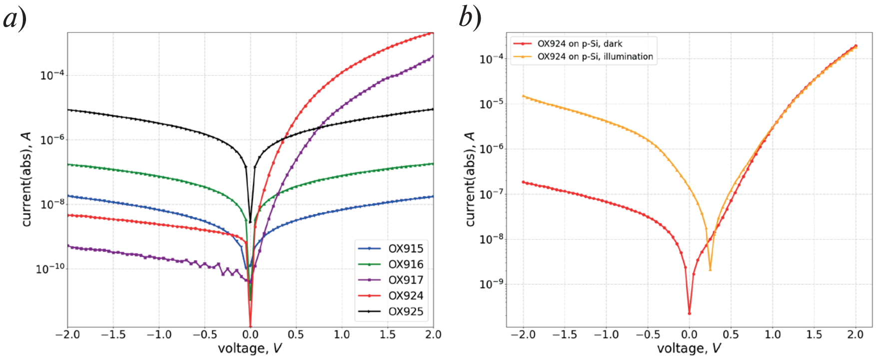

Fig. 1. Current-voltage characteristics for structures Au/BP/n-Si grown under different conditions (*a*) and for Au/BP/p-Si (*b*)

Capacitance-voltage characteristics were measured at 100 kHz signal frequency in the reverse bias voltage for samples grown on n-Si substrate, the obtained results are shown in the Fig. 2. It can be seen that the capacitance of the sample Ox915 grown without an additional hydrogen flow and with low plasma power is weakly dependent on the applied voltage under different temperatures, thus it could be considered an insulator. At the same time, the noticeable drop of the capacitance that shifts left in the direction of lower voltage bias with the increasing the temperature is present in the other samples. This feature indicates the presence of potential barrier at BP/n-Si heterojunction. An additional concentration profiling [5] was performed for three samples on the basis of the measurements, the dependencies are presented in the Fig. 3. At low temperature (80–120 K) value of charge carrier concentration is constant and ~ 10^{15} cm^{-3} that indicates profiling of silicon substrates. However, with increasing of temperature capacitance increases, and additional step appeared at higher amplitude of voltage. Further, at room temperature free

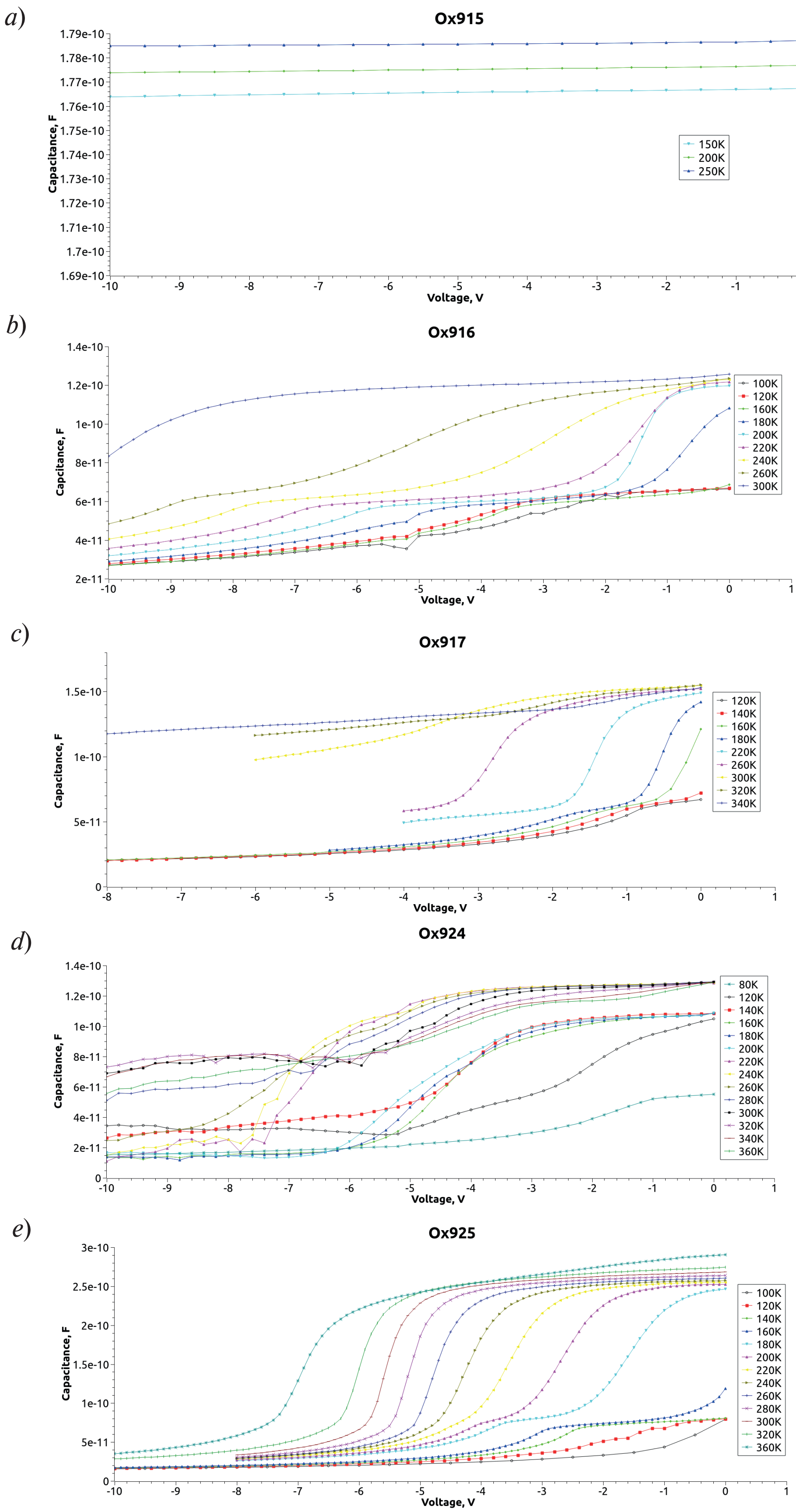

Fig. 2. Capacitance-voltage characteristics dependent on the temperature for structures Au/BP/n-Si grown under different conditions

charge carrier concentrations drop drastically with the increasing the depth inside the sample, from orders of ~ 10^{17} cm^{-3} to ~ 10^{15} cm^{-3} already on the distance of about a micron. Taking into account such parameters as the thickness of the samples (see Table) and the given charge carrier concentration in silicon substrate (which is also of the order of ~ 10^{15}), such a form of concentration profiles could be associated with the presence of space charge region at interface BP/n-Si due to activation of thermal conductivity in BP.

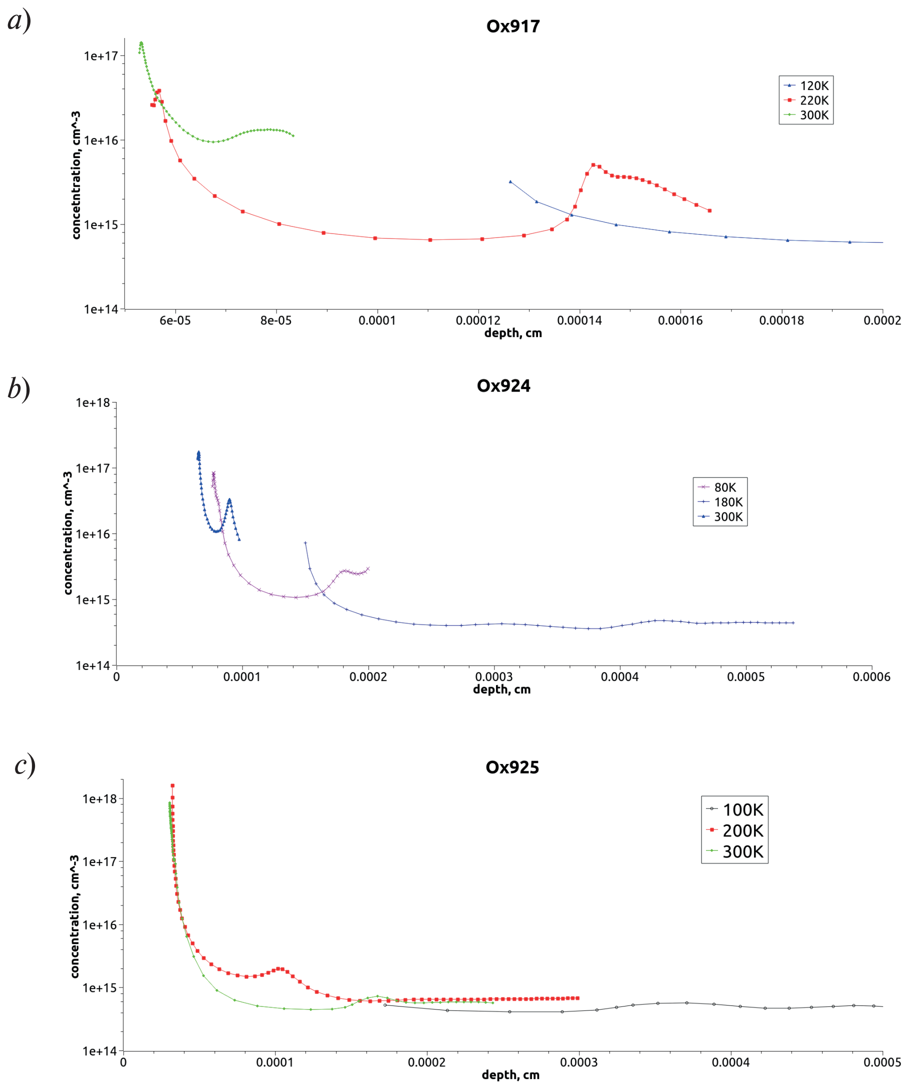

Fig. 3. Concentration profiling data extracted from voltage-capacitance characteristics of structures Au/BP/n-Si grown under different conditions

Conclusion

In this work the electrophysical properties of BP layers grown by continuous PECVD method with flow of diborane under different conditions were investigated. It was found out, that high plasma power and an additional flow of hydrogen in the growth chamber allow to obtain the rectifying behavior on Au/BP/n-Si structures since BP acting as an n-doped semiconductor. Capacitance-voltage characterization revealed the presence of the space charge region with the potential barrier at interface BP/n-Si in the grown samples, and BP conductivity depends on temperature. The future research is to be devoted to exploration of capacitance properties of BP/Si heterojunction by admittance and deep-level transient spectroscopy.

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