Black Phosphorus Field Effect Devices: A Review

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Abstract— Black Phosphorus, an allotrope of Phosphorus shows an anisotropic structure at monolayer known as phosphorene, which gives rise to some interesting phenomena such as a semiconducting behavior and bipolar tendencies. With the disadvantage of being extremely ambient sensitive, there are several ways to protect the material from humidity and oxidation while exploiting its properties to make electronic devices. These properties can be used to fabricate transistors which could in near future be used in applications such as Flexible Electronics, Energy Efficient Devices, Transparent, wearable devices.

In this review we would look at different metals used to make contact with the phosphorene flakes and various device geometries used to study the properties of the material.

Index Terms—Black Phosphorus, Phosphorene, Semiconductor, 2D material, Field Effect Transistor, Contact Resistance.

I. INTRODUCTION

Phosphorene is a two-dimensional material and allotrope of phosphorus. Phosphorene can be viewed as a single layer of black phosphorus, much in the same way that graphene is a single layer of graphite. Phosphorene is predicted to be a strong competitor to graphene because, in contrast to graphene, phosphorene has a band gap.[1].
Monolayer Phosphorene was first isolated in 2014[2].

Its high carrier mobility, high optical and UV absorption, and other attractive properties, which are of particular interest for optoelectronic applications. Unlike graphene, phosphorene has an anisotropic orthorhombic structure that is ductile along one of the in-plane crystal directions but stiff along the other. This results in unusual mechanical, electronic, optical and transport properties that reflect the anisotropy of the lattice.[1]

Measuring the electrical properties of the 2D materials is done with the device geometry of Field Effect Transistor.

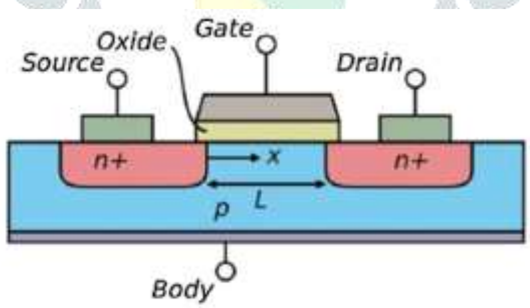

Fig. Field Effect Transistor Geometry

To study the quantum phenomenon of quanyum hall effect, the devices are fabricated using the Hall Bar Geometry.

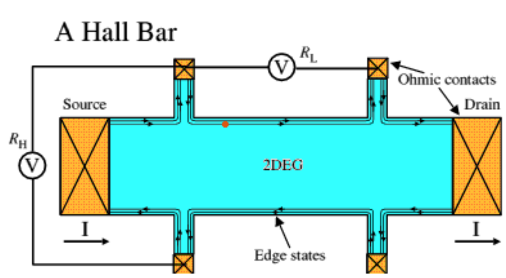

Fig. Hall Bar Geometry

II. METALS FOR CONTACT

To make contact with the layer of Phosphorene, several contact materials have been tested by different research groups. Most commonly used metal to make contact with 2D materials is gold and it is used for its extremely low resistance, though it is seen that at the contact, various metals such as Chromium, Palladium, Titanium,etc. used with Gold, show slightly better contact resistances than just gold. Some of the optimal measured contact resistances are given in the table.

Table: Notable metal contacts and Contact Resistances

Ref	**Metals**	**4 probe resistance**	**2 probe resistance**	**No**
Du et al ACS nanovol 8 no 10 10035-10042 2014	Ni Pd		1.75 (+/-) 0.06 Ω .mm 3.15 (+/-) 0.15 Ω . mm	[3]
Liu et al ACS Nano vol 8 no 4 4033-4041 2014	Ti/Au (20/60nm)		42.24 Ω . mm	[4]
Liu et al IEEE ELECTRON DEVICE LETTERS, VOL. 35, NO. 7, JULY 2014	Ni/Au (20/60nm)		14.902 Ω . mm	[5]
Gillgren et al 2D Mater. 2 (2015) 011001	Cr/Au (10/100nm)	6.745 Ω .mm (Vg =-70)		[6]
Haratipour et al IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 4, APRIL 2015	Ti/Au (5/100nm)		2.8005 Ω . mm	[7]
Das et al *ACS Nano*, **2014**, *8* (11), pp 11730–11738	Pd Ni Ti		1.75 Ω .mm 3.15 Ω .mm 4.85 Ω .mm	[8]
Li et al NATURE NANOTECHNOLOGY | VOL 9 | MAY 2014	Cr/Au (5/60nm)		125 kΩ (-30V gate voltage) 199 MΩ (20V gate voltage)	[2]

III. DEVICES

Making contact with the black phosphorus flake with various metals in FET geometry to measure device gating and quantum phenomena like quantum hall effect and quantum capacitances can be measured with hall bar geometry.

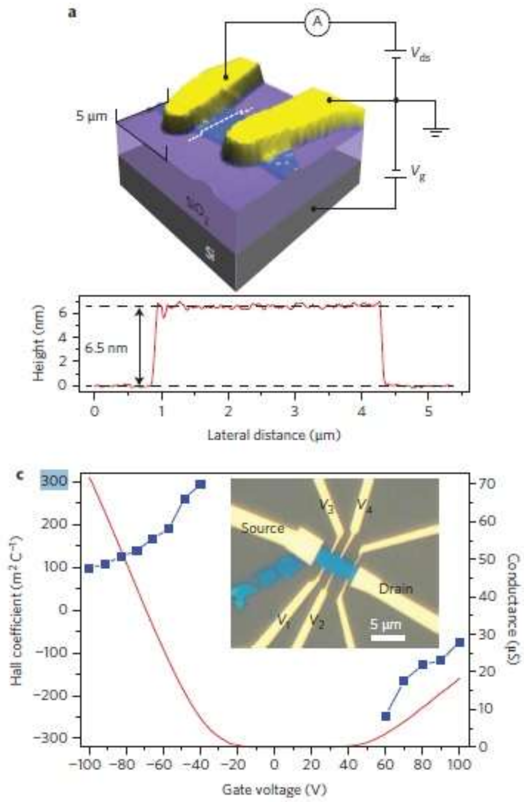

Fig.Source–drain current (on a logarithmic scale)as a function of gate voltage obtained from a 5-nm-thick device on a silicon substrate with 90 nm SiO2 at room temperature, with drain–source voltages of10 mV (red curve) and 100 mV (green curve). Channel length and width of the device are 1.6 mm and 4.8mm, respectively. Drain current modulation up to_105 is observed for both drain–source biases on the hole side of the gate doping, with a subthreshold swing (the slope of the black dashed line) of 4.6 Vper decade. A slight turn-on at the electron side is also observed[2].

Li et al[2] have put gold contacts on the bare Black phosphorus flake to make a field effect transistor with a pair of source and drain with six electrodes.
Atomic force microscopy of the flake shows 6.5nm of thickness of the flake.
Magnetoresistance sweep against gate voltage gives hall coefficient curve shown in above image.

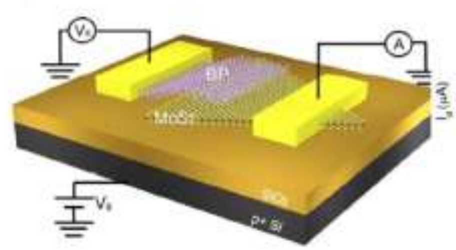

Fig. BP and MoS_2Transistor[1]

Carvalho et al[1]. have stacked a black phosphorus flake on an MoS_2 flake such that source makes contact with BP and drain makes contact with MoS_2 where contacts are made with chrome and gold metal electrodes.

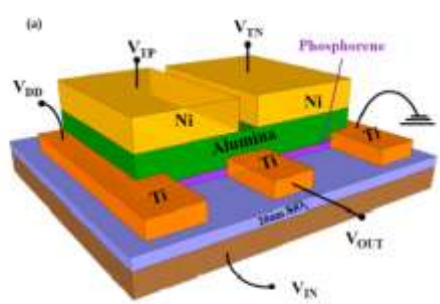

Fig. P & N doped BP transistor with Ti contact[8]

Das et al[8] have made contact with the phosphorene in a unique way using titanium as contact metal and fabricating 2 devices with a common gate and opposite dopingsparameters.giving a way to study the ambipolar nature of black phosphorus in a comparative way.

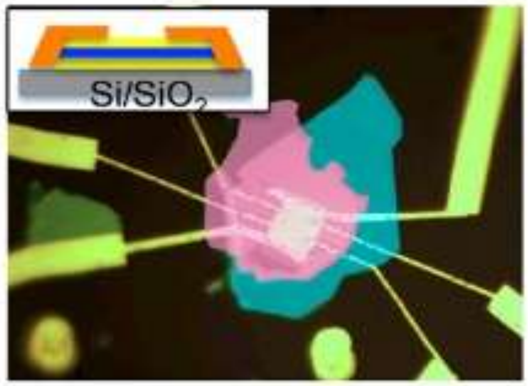

Fig. BN-BP-BN FET device[6]

In the false colored optical microscope image of the device by Gillgren et al [6] it is shown to have a black phosphorus flake sandwiched between two flakes of boron nitride turning the device ambient proof protecting the BP flake from humidity and oxidation. Contacts have been made with chrome and gold giving 4 probe contact resistance of 6.4 Ω.

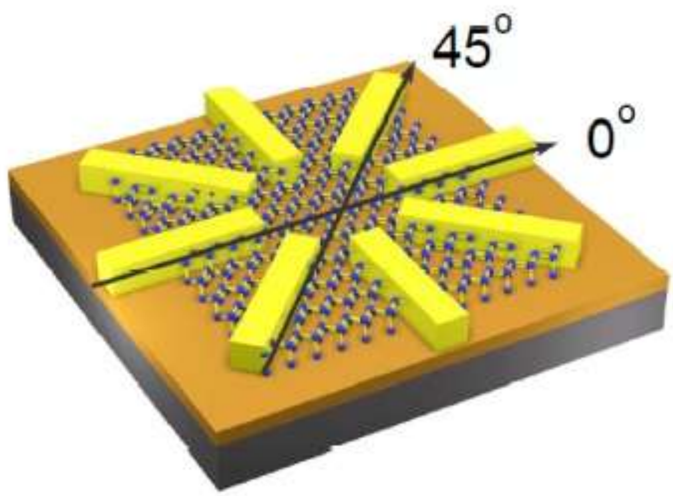

Fig. Electrodes placed at 45 degrees on BP flake.[10]

Liu et al [10] have developed a method to find out the crystal orientation of BP flakes and use it to calibrate device geometry. For this, they have placed 8 gold electrodes on the BP flake with 45 degrees between each electrode. With a varying angle, they have observed varying gating in the electrodes.

IV. Conclusion

In conclusion, we can see that the ambipolar properties of Black phosphorus thin flakes can be used to make effective semiconductor Field Effect Devices. To achieve the lease contact resistance to observe the quantum properties of the material, contacts made with Chromium and Gold are most effective.

V. Future Prospects

The devices made with the 2D materials such as graphene, phosphorene, MoS_2, Boron Nitride, etc. can be used to utilize the quantum properties of these materials. Also, because of their mechanical properties and size, they can be used to build smaller devices with varying properties like flexibility, transparency, wearability, energy efficiency, etc.

VI. References

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