Infrared Photodetectors with Two Dimensional Materials

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Abstract:

In this work, a new heterostructure photodetector has been designed using monolayer graphene and varying thicknesses of molybdenum disulfide. This device could provide sensitivity in the infrared (IR) region optimal for optical communication, 1550 nanometers (nm), while maintaining low dark current. Monolayer graphene grown by chemical vapor deposition (CVD) has been patterned onto mechanically exfoliated molybdenum disulfide (MoS_2) and titanium-gold (Ti-Au) contacts made to both materials. Initial electrical characterization of the devices has been performed. The resulting resistance and linearity of the contacts agree with predictions. Infrared probing of the device at 1550 nm indicates either more surface area or a different wavelength is required.

Introduction:

As computer processor speed rises exponentially, the bandwidth required for inter-processor communication grows as well. Integrated optoelectronics may solve the interconnect bandwidth bottleneck. The three necessary components are infrared transmitters, modulators and detectors. The field of infrared transmission is already a mature science, and some progress has been achieved with experimental infrared modulators with signs of future success. The remaining piece of the puzzle is suitable infrared photodetectors. The unique properties of two dimensional (2D) materials could be the key to their construction, helping to realize the next generation of high-speed optical communications.

Device Concept:

Previous attempts to construct an IR photodetector with 2D materials focused on graphene, which absorbs radiation over a wide wavelength range spanning from the far infrared to the visible. However, graphene is problematic because of its high conductivity. Any voltage applied to collect charge carriers freed by radiation will also cause non-photoinduced current, or dark current. This dark current is on the same order as the photocurrent from an ordinary source, resulting in a low signal-to-noise ratio. To circumvent this issue, MoS_2 was incorporated

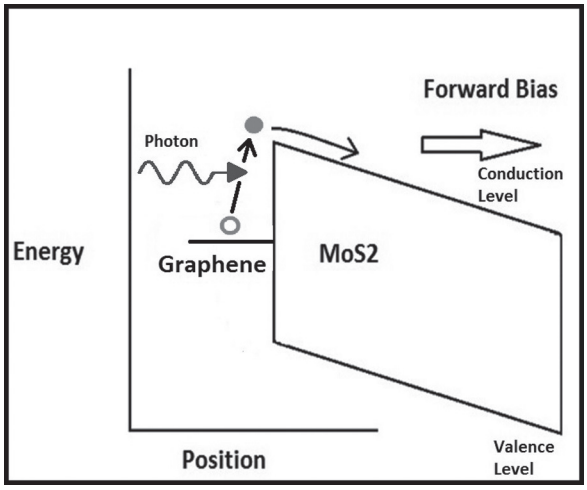

Figure 1: Envisioned operation in the new device. An infrared photon induces a graphene carrier to make the leap into the MoS_2's conduction band, where it is carried away by the applied bias, thus producing a signal. The photon must carry at least enough energy to overcome the graphene-MoS_2 barrier.

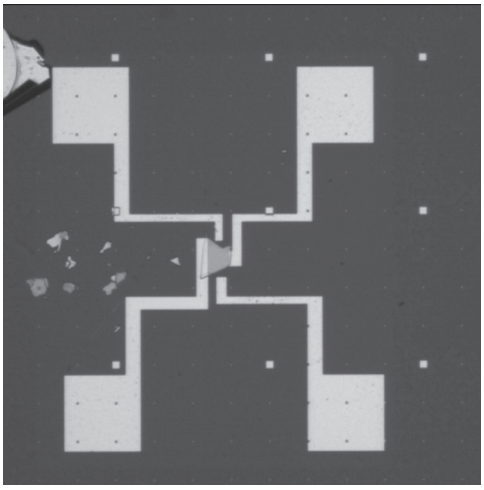

Figure 2: A completed device. The central piece is a flake of MoS_2 of approximately 50 µm by 50 µm. Atop this is a nearly-transparent piece of graphene. A pair of Ti-Au contacts overlaps the edge of each material.

into the device to introduce a band-gap, which minimizes dark current, thus improving the signal. It is believed that the Fermi level in graphene is between the conduction and valence bands of bulk MoS_2. Since the gap exceeds the energy contained in a 1550 nm photon, it should be possible to gate the device so as to induce an energy barrier between the graphene and MoS_2 which corresponds to 1550 nm. This is both the device's absorption and noise-reduction mechanism.

Fabrication Sequence:

A sequence of fabrication steps was developed to produce these devices. The first step was using electron-beam lithography (EBL) and electron beam evaporation (EBE) to attach an alignment grid onto the chosen substrate — in this case, a silicon dioxide and silicon wafer. The second step was mechanical exfoliation of MoS_2 onto the wafer and location of suitable flakes. After their locations were mapped out, a large sheet of monolayer graphene was removed from its copper foil and placed over the substrate. Then EBL was used to pattern a resist polymer onto the flakes to protect certain areas of the graphene sheet. A light oxygen plasma removed the uncoated areas of graphene. Finally EBL and EBE were applied once more to lay down metallic contact pads on the graphene and MoS_2.

Characterization:

After some devices were completed, they were tested by measuring the current induced by applying voltages between the graphene-graphene, graphene-MoS_2, and MoS_2-MoS_2 contact combinations. The resulting I/V characteristics showed that the electrical contacts were alive and behaved as expected. The graphene-graphene characteristic was linear, indicating an Ohmic contact with a resistance of approximately 27 kΩ. The MoS_2-MoS_2 and graphene-MoS_2 tests, on the other hand, exhibited behavior reminiscent of a Schottky barrier, producing asymmetric I/V characteristics whose linear approximations give resistances of approximately 67 MΩ and 33 MΩ. These preliminary results suggest photodetector should be detectable with this device.

However when the same characterizations were performed with an IR laser incident on the sample, no significant change was recorded. There are several possible explanations for this. First, the testing stage used required that the fiber carrying the IR signal be several millimeters over the sample, causing the beam to diverge drastically. Another possibility is that the junction region will not absorb 1550 nm light. This could be rectified by gating the junctions appropriately to shift the Schottky barrier. Another possibility is that the device's small surface area did not allow enough absorption for an appreciable photocurrent, but this seems less likely as other detectors of a similar size have been fashioned from graphene alone.

Future Work:

There is a vast amount of progress left to be made. The very first step, as mentioned above, is to achieve photodetection in the ideal region near 1550 nm. Subsequently various optimizations must be performed to determine the ideal size, thickness and possibly shape of the MoS_2 flakes that should be used. Monolayer, or 2D, MoS_2 should be an area of special interest due to its unique band structure. If these devices can be made as effective as is hoped, then a more efficient exfoliation process must also be found so as to make mass production a more realistic goal.

Conclusions:

A new heterostructure photodetector using 2D materials has been proposed, a fabrication sequence developed and prototypes constructed. Initial characterizations show promise but much work remains before actual photodetection is measured. If the potential of these devices is realized they could replace current electronic communications systems, greatly enhancing computational data transfer bandwidth.

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