Electronic properties of germanane field-effect transistors


Published in:
2D Materials

DOI:
10.1088/2053-1583/aa57fd

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2017

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Electronic properties of germanane field-effect transistors

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2017 2D Mater. 4 021009
(http://iopscience.iop.org/2053-1583/4/2/021009)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 129.125.148.206
This content was downloaded on 29/06/2017 at 14:53

Please note that terms and conditions apply.

You may also be interested in:

Photoconductivity of few-layered p-WSe2 phototransistors via multi-terminal measurements
Nihar R Pradhan, Carlos Garcia, Joshua Holleman et al.

Water activated doping and transport in multilayered germanane crystals
Justin R Young, Basant Chitara, Nicholas D Cultrara et al.

Atomically thin semiconducting layers and nanomembranes: a review
Mircea Dragoman, Daniela Dragoman and Ion Tiginyanu

Two-dimensional hexagonal semiconductors beyond graphene
Bich Ha Nguyen and Van Hieu Nguyen

Isolation and characterization of few-layer black phosphorus
Andres Castellanos-Gomez, Leonardo Vicarelli, Elsa Prada et al.

Chemical doping of MoS2 multilayer by p-toluene sulfonic acid
Shaista Andleeb, Arun Kumar Singh and Jonghwa Eom

First principles study of fluorine substitution on two-dimensional germanane
Lin Hu, Jin Zhao and Jinlong Yang

Toward high-performance two-dimensional black phosphorus electronic and optoelectronic devices
Xuefei Li, Xiong Xiong and Yanqing Wu

Synthesis, properties and applications of 2D non-graphene materials
Feng Wang, Zhenxing Wang, Qisheng Wang et al.
Electronic properties of germanane field-effect transistors

B N Madhushankar¹, A Kaverzin¹, T Giousis², G Potsi¹,², D Gournis³, P Rudolf¹, G R Blake¹, C H van der Wal¹ and B J van Wees¹

¹ Zernike Institute for Advanced Materials, University of Groningen, Groningen, NL-9747AG, The Netherlands
² Department of Materials Science and Engineering, University of Ioannina, 45110 Ioannina, Greece
E-mail: m.bettadahalli.nandishaiah@rug.nl

Keywords: two-dimensional materials, electronic devices, electronic properties and materials, opto-Electronics, germanane, transistor, semiconductors

Supplementary material for this article is available online

Abstract

A new two dimensional (2D) material—germanane—has been synthesised recently with promising electrical and optical properties. In this paper we report the first realisation of germanane field-effect transistors fabricated from multilayer single crystal flakes. Our germanane devices show transport in both electron and hole doped regimes with on/off current ratio of up to $10^3$ ($10^4$) and carrier mobilities of $150 \text{ cm}^2 \left( \text{V s} \right)^{-1}$ ($70 \text{ cm}^2 \left( \text{V s} \right)^{-1}$) at 77 K (room temperature). A significant enhancement of the device conductivity under illumination with 650 nm red laser is observed. Our results reveal ambipolar transport properties of germanane with great potential for (opto)electronics applications.

The exceptional transport properties of graphene have generated an immense impulse that has stimulated the scientific community to study other layered Van der Waals materials [1–3]. Graphene analogues such as germanane, silicene, and stanene, as a separate family with hexagonal crystal structures, deserve careful consideration as they promise high quality charge transport properties, similar to their carbon predecessor [4, 5]. The hydrogenated form of germanene, known as germanane, has recently been synthesised for the first time by Bianco et al [9]. The crystal structure of germanane consists of a hexagonal germanium lattice with hydrogen atoms (H) covalently bonded to every germanium atom (Ge) as shown in figure 1(a). Germanane is of particular interest, because in addition to high quality charge transport it is expected to have a band gap, similar to its graphene analogue graphene [6–8]. In [9] the band gap of the germanane was experimentally estimated from diffuse reflectance absorption spectroscopy to be around 1.59 eV, close to the calculated values reported in [6–8].

Until now the number of available publications on this material is still very limited, covering theoretical investigation of the band structure [6–8, 10, 12] and very preliminary electrical characterisation [11, 13, 14]. The electron mobility, limited by electron-phonon scattering, was calculated to be around $20000 \text{ cm}^2 \left( \text{V s} \right)^{-1}$ at room temperature [9], which is strongly appealing for germanane to form a good basis for future application devices.

To prepare the multilayer germanane flakes from powder we followed the protocol from Bianco et al [9], which involves the topochemical deintercalation of CaGe₂. The quality of our germanane powder has been confirmed by a set of characterisation techniques including x-ray diffraction, FTIR spectroscopy, Raman spectroscopy and DRA measurements (see supplementary information stacks.iop.org/TDM/4/021009/mmmedia), which fully verify that the synthesised material is indeed germanane. The prepared powder was further processed to fabricate transistors. Germanane flakes were mechanically cleaved down to thicknesses ranging from 15 nm up to 90 nm and placed on top of a 300 nm Si/SiO₂ substrate. Ti/Au contacts (5 nm/100 nm) were made via standard PMMA-based e-beam lithography, as shown in the optical image of a typical device in figure 1(b). The thickness of the flake was determined by atomic force microscopy (AFM) as shown in figures 1(c) and (d) to be ~60 nm. Further details of the fabrication protocol are given in the methods section.

As initial electrical characterisation we performed resistance measurements at room temperature in the linear regime (the measured voltage scales linearly with the applied current). We measured the voltage $V$ in a 2-terminal configuration when a constant current of 2 nA was supplied, shown as the blue curve in figure 2(a). The signal was measured as a function of the applied gate voltage $V_g$, revealing a peak-like feature. The appearance of this maximum is associated with tuning of the Fermi
Figure 1. (a) Schematic representation of a germanane monolayer (top and side views) with Ge atoms (blue) at the corners of hexagons and H atoms (yellow) bonded to Ge. (b) Optical image of the germanane flake based device on top of a Si/SiO$_2$ substrate with Ti/Au electrodes (Scale bar is $3\mu$m). (c) AFM image of the germanane transistor. (d) The height profile is plotted along the red line as shown in panel (c) giving the flake thickness to be $\sim 60$ nm.

Figure 2. (a) Measured signal $V$ plotted for 2-terminal (blue), 3-terminal (red) and 4-terminal (black) configurations as a function of the gate voltage. The 3-terminal measurements were performed using both contacts 18 (triangles) and 19 (diamonds). The applied constant current between source and drain was 2 nA, and the measurements were performed at room temperature. (b) 2-terminal measurements as a function of $V_G$ performed using different distances between the contacts while keeping the same source contact. The resistance values at the curve maxima scale approximately with the channel length (for the sample geometry, see figure 1(b)). $I = 2$ nA. (c) 2-, 3- and 4-terminal measurement configurations allow the contact and channel-related resistances to be extracted separately. (d) Room temperature conductance calculated from the 4-terminal measurement shown in panel (a) The red line represents a linear fit resulting in a mobility of $\sim 30$ cm$^2$ (V·s)$^{-1}$. 

2D Mater. 4 (2017) 021009
level of the material in the band gap, implying that the studied device is ambipolar or, in other words, indicating the possibility to electrically dope it with both holes and electrons. It is worth noting here that the position of the maximum close to $V_G = 0$ V indicates a relatively low intrinsic doping of the material.

A semiconductor, when brought into direct contact with a metal, forms a Schottky barrier which usually results in a relatively high contact resistance and thus affects the measured 2-terminal $V(V_G)$ dependence. To circumvent the influence of the resistive contacts and distinguish between channel and contact properties, 4-terminal electrode configuration was used. In figure 2(a) different multiterminal measurements (see figure 2(c) for schematics of configurations) are shown together for a clear comparison. The 2-terminal measurement contains contributions from both the channel resistance and the two interface resistances (see supplementary information for the resistance model used) and is seen to be asymmetric with respect to the peak position. In contrast, the 4-terminal voltage shows a much more symmetric dependence on $V_G$, as one would expect for a semiconducting material with similar electron and hole transport properties. The difference between the 2-terminal and 4-terminal curves is ascribed to the contact resistances and can be probed more directly in a 3-terminal configuration. The measured dependencies indeed indicate that the observed asymmetry is related to the transport through or in the vicinity of the contact interface and can be explained by the presence of expected Schottky barriers at each contact interface. The degree and sign of the asymmetry (as for the height and position of the Schottky barrier itself) are determined both by the Fermi level positions in the adjacent regions and by the properties of the interface such as the density of impurity states. We note that in addition to formation of the Schottky barrier, the metal contact can also lead to modification of the underlying bulk channel. In this scenario the contact contribution cannot be excluded even in a 4-terminal configuration (see supplementary information for more details).

An alternative way to differentiate between the channel and contact properties is to measure 2-terminal resistances for different channel lengths. In figure 2(b) we plot 2-terminal resistances measured with fixed source contact 17 while the drain contact was varied over all possible configurations (see figure 1(b)). The central portion of the curves around the maxima scales approximately with the channel length $L$, while for large positive gate voltages the measured signals saturate at values that are independent of $L$. This further confirms a clear distinction between the channel associated resistance and the asymmetric contribution attributed to the contact regions, which influences the measurement mostly at positive $V_G$.

Next we replott the measured 4-terminal voltage in terms of the channel conductance ($I/V$) as a function of applied $V_G$, in figure 2(d). The obtained dependence is symmetric, emphasizing again the ambipolar nature of the transport. Assuming a linear dependence of the conductance on carrier concentration and that the geometrical capacitance per unit area of the bottom Si/SiO$_2$ gate is 11 nF cm$^{-2}$, we estimate a carrier mobility of $\sim 30$ cm$^2$ (V$\cdot$s)$^{-1}$ at room temperature.

In order to explore the higher carrier concentration regime, we extended the range of used gate voltages up to ±50 V. At the maximum $V_G$ range, an on/off current ratio for the holes is found to be $\sim 10^4$ at room temperature and $\sim 10^5$ at 77 K (see supplementary information available at stacks.iop.org/TDM/4/021009/mmedia). At $|V_G| > 10$ V a prominent hysteretic behaviour develops which is most pronounced at higher temperatures where the difference between the positions of the minima for opposite sweeping directions can be as large as $\sim 60$ V for a sweeping range of ±50 V (at a sweeping rate of $\sim 0.1$ V s$^{-1}$). Such hysteresis indicates the presence of a substantial number of charge trap states within the range over which the Fermi level varies. Under an applied gate voltage these traps become activated/deactivated and can modulate the effective doping level of the system, thus affecting the shape of the conductivity dependence. At lower temperatures charge traps become frozen, considerably diminishing the degree of hysteresis and improving the reliability of the mobility estimation. For clarity, in our subsequent analysis below we use measurements performed with the same sweep direction from positive to negative $V_G$ unless stated otherwise (figure 3). The mobility is estimated from the linear high carrier concentration part of the conductance dependence as a function of $V_G$ and is plotted as a function of temperature in the inset. The observed increase in mobility with decreasing temperature could suggest a significant reduction of the contribution of the phonon scattering to the transport properties of carriers. Alternatively such temperature dependence of the extracted mobility can be artificially induced by the temperature dependent hysteretic behaviour of the measured conductance. However, such mobility extraction is still reliable at low temperatures where the observed hysteresis is minimal. Below about 170 K, the mobility saturates at $\sim 150$ cm$^2$ (V$\cdot$s)$^{-1}$. This exceeds the value estimated from the room temperature, low $V_G$ range dependence (figure 2(d)), presumably due to the fact that in the low $V_G$ range the system does not yet reach the linear conductivity regime as the Fermi level is still in the transition from the band gap to the valence band. Furthermore, electron transport is observed to be significantly suppressed compared to hole transport due to the presence of both hysteresis and the contact contribution in the 2-terminal measurement configuration as discussed earlier. Therefore, the set of performed measurements does not allow us to characterise the temperature dependence of the electron transport.

To further demonstrate the transistor action of germanane in the non-linear regime, we repeated the 4-terminal voltage measurements using applied currents up to 100 nA, as shown in figure 4. In this regime
the voltage drop along the channel becomes comparable with the applied gate voltage and therefore creates an easily observable additional doping effect that changes along the length of the transport channel. These transport measurements probe an effect that can be approximated to first order by an average doping value, i.e. an extra gating of $V/2$. This means that under an applied voltage $V$ across the channel, the measured dependencies are expected to be shifted by $V/2$. Such a shift is indeed seen in figure 4. For instance, when the applied bias current is $100 \text{nA}$ the voltage across the sample at the maximum is $\sim 8 \text{V}$. The position of the maximum is shifted with respect to its linear regime position (see figure 2(a)) by $\sim 5 \text{V}$, which is close to the expected $8/2 \text{V}$. The small degree of asymmetry between positive and negative applied currents indicates intrinsic asymmetry in the device and is further discussed in the supplementary information.

So far we have presented measurements performed in the dark, thus avoiding influence of ambient light on the transport characteristics of germanane. However, the theoretical studies [6–8] suggest the presence of a direct band gap in germanane, which implies a substantial response of the material to light excitation of the appropriate wavelength. Accordingly, we performed an experiment where the channel conductance in 4-terminal configuration was measured both in the dark and under illumination, shown in figure 5. For the light source we used a red laser with a wavelength of $650 \text{nm}$ and an intensity of $\sim 40 \text{mW cm}^{-2}$. The increase of the conductance under illumination over a certain gate voltage range (swept from negative

Figure 3. The 2-terminal conductance for contacts 18 and 19 is plotted as a function of $V_G$ at different temperatures. The orange line represents an example of a linear fit for the extraction of hole mobility. The perceived 2-terminal hole mobility is expected to be close to the actual channel mobility because (as shown in figure 2) the contact contribution at negative gate voltages is minimal. The gate voltage was swept from positive to negative values. Inset: 2-terminal hole mobility extracted from the data plotted in the main panel, shown as a function of temperature.

Figure 4. 4-terminal voltage measured as a function of $V_G$ for a set of different bias currents at room temperature. The current was applied between contacts 17 and 7, while the voltage was measured between contacts 19 and 13.
to positive values) can suggest the excitation of extra carriers by photons as it happens in direct band gap materials. However, the substantial hysteresis in the system that is also observed indicates the presence of charge traps in the channel or in its vicinity. Such trap states can also be optically active and can influence the response to the illumination. The time responses of a trap system and a band electron system are expected to be significantly different because band electron systems reach equilibrium relatively fast compared to trap states. In the inset to figure 5 we show the electrical response measured in 4-terminal configuration as a function of time when the laser light was modulated with a chopper at a frequency of 4 Hz. Double exponential fitting clearly indicates two components with characteristic times of $t_1 \approx 0.20$ s and $t_2 \approx 8.3$ ms. Since the trap-associated processes are expected to be much longer than those associated with band carriers, we interpret the appearance of a long time $t_1$ as an indication of trap states in the vicinity of the channel. The short time $t_2$ is consistent with the bandwidth limitation of our electrical measurement circuit (RC time limitation), which masks the real time scale of the fast response. The time response of band electrons in similar systems is typically faster than 1 ns (for GaAs see [15]). Therefore, further investigation with a higher frequency bandwidth is needed in order to characterise the photoresponse of the device at short timescales.

In conclusion, in this work we have demonstrated the realisation of single crystal germanane field-effect transistors with a current on/off ratio in the range of $10^4$–$10^5$, depending on the temperature. By employing various multiterminal measurement configurations, we have clearly separated the transport properties of the germanane channel from those of the contacts. Low gate voltage dependence measured at room temperature clearly reveals that germanane exhibits ambipolar behaviour. We have found a low bound for the hole mobility to be $70$ cm$^2$V$^{-1}$s$^{-1}$ at room temperature which further increases to $150$ cm$^2$V$^{-1}$s$^{-1}$ below 150 K. Moreover, our study of the influence of light illumination confirms the high responsivity of the material, although further investigations are needed to fully characterise the photoresponse.

**Methods**

Germanane (GeH) was synthesised by the topotactic deintercalation of $\beta$-CaGe$_2$ in aqueous HCl at $-40$ °C based on a method reported previously [9, 16–18]. The precursor phase $\beta$-CaGe$_2$ was prepared by sealing a stoichiometric $1:2$ ratio of calcium (granular Ca with purity 99 % from Sigma-Aldrich) and germanium (Ge powder with purity 99.99 %, Sigma-Aldrich) in a cylindrical alumina crucible (external diameter of 11 mm) enclosed in an evacuated fused quartz tube (internal diameter of 12 mm). The mixing of the two metals and the filling of the crucible was performed in a glove box under nitrogen atmosphere. The sealed quartz tube was then placed in a box furnace and the following temperature profile was employed: (1) heating to 1025 °C within 2 h at a rate of 8.3 °C min$^{-1}$; (2) homogenization at 1025 °C for 20 h; (3) slow cooling to 500 °C at a rate of 0.1 °C min$^{-1}$ and finally (4) cooling further to room temperature at a rate of 0.2 °C min$^{-1}$. Small crystals (2–6 mm) of CaGe$_2$ were collected and treated with an aqueous HCl solution 37% w/w (12 M) at $-40$ °C under stirring for 7 d. The final product (GeH) was then separated.
by centrifugation, washed several times with distilled water (and finally methanol), and left to dry under vacuum. No trace of a calcium signal was detected in the measured energy-dispersive x-ray spectrum of our sample, confirming the successful topotactic deintercalation of $\beta$-CaGe$_2$ and the formation of germanane (GeH) product.

The flakes were isolated via mechanical exfoliation of the synthesised powder. With an optical contrast microscope we were able to differentiate flakes with different thicknesses and we chose those with an appropriate size and shape. Ti/Au electrodes were fabricated via standard electron beam lithography using PMMA as a resist layer. Solvent residue was evaporated from the resist film by baking at 150 °C for 90 s. It was shown in [9, 16] that prolonged temperature treatment of germanane above 75°C in 5% H$_2$/Ar can cause an amorphisation process. To exclude the possibility that brief heat treatment might cause a change in the crystal structure, we made a follow-up device (sample 2) without baking, which showed quantitatively the same behaviour as sample 1 (see supplementary information). Of four prepared devices, only two were found to be electrically connected by the electrodes, presumably due to the fast oxidation of the germanane surface. Both working devices were prepared within a relatively short time period of $\sim$12 h between the exfoliation and contact deposition in order to minimise the oxidation effect. All electrical measurements were performed in a DC current mode with the use of a Keithley 2410 source measure unit in both a vacuum chamber and a cryostat. The samples were stored and measured in vacuum with pressures of below 10$^{-5}$mbar in the sample space.

Acknowledgments

We would like to gratefully acknowledge D M Balazs and Prof M A Loi for their help with UV-Vis-NIR/DRA measurements. We would also like to thank Prof W R Browne for providing the Raman system for our measurements and M Gurram for his help in electrical measurements of sample 2. BNM would like to thank B N Kiran Shankar for illustrating the schematic of figure 1(a). For the technical support the authors would like to thank M de Roosz, H Adema, T Schouten and J G Holstein. This work is funded by the European Union Seventh Framework Programme under ‘Graphene Flagship’ (Grant No. 604391), the Dutch Foundation for Fundamental Research on Matter (FOM) and Dieptestrategy funding from the Zernike Institute for Advanced Materials. GP acknowledges support from the Ubbo Emmius Fund of the University of Groningen.

Author contributions

BvW, PR and DG conceived and designed the project. TG and DG synthesised the material and performed FTIR spectroscopy. GRB and GP did an XRD and DRA spectroscopy and analysis. BNM fabricated the devices. BNM and AK performed electrical characterisation, did the analysis and drafted the manuscript. CHW contributed to the analysis of optical experiments. BvW and PR contributed to the analysis, discussions and supervision of the project. All the authors gave comments on the manuscript.

References