Bias-Switchable Photoconductance in a Nanoscale Ge Photodetector Operated in the Negative Differential Resistance Regime

Masiar Sistani, Raphael Böckle, Maximilian G. Bartmann, Alois Lugstein, and Walter M. Weber*

Cite This: ACS Photonics 2021, 8, 3469–3475

ABSTRACT: Recent advances in nanoscale optoelectronic Ge devices have exposed their enormous potential for highly sensitive visible and near-infrared CMOS compatible photodetectors. In this respect, Ge nanowires, due to their nanocylinder resonator shape, have established themselves as a promising platform to significantly enhance the performance of photodetectors. Here, we present a highly sensitive polarity switchable Ge nanowire photodetector embedded in a monolithic and single-crystalline metal–semiconductor nanowire heterostructure. Operated in the negative differential resistance regime, effective dark current suppression up to a factor of 100 is achieved. In this configuration, a bias-switchable positive and negative photoconductance is observed and systematically analyzed. Further, a remarkably strong polarization anisotropy with a maximum TM/TE ratio of 33 was found for positive photoconductance. Most notably, presenting a Ge-based photodetector combining switchable photoconductance and effective dark current suppression may pave the way for advanced applications, including highly resolved imaging and light effect transistors.

KEYWORDS: germanium, nanowires, photogating, switchable photoconductance, negative differential resistance

Group IV based photonic components are a very active area of research with extensive interest in CMOS compatible photodetectors. In this respect, Ge is considered a key material in the visible and near-infrared region, covering the C-band optical communication range. In terms of detector geometry, bottom-up, vapor–liquid–solid (VLS) grown Ge nanowires (NWs) have gained particular attention. Aside from physical advantages in their optoelectronic structure, NWs are also of foremost interest due to their technologically relevant scaling capability and compatibility with CMOS platforms. Most notably, applied for photodetectors, NWs can be viewed as nanocylinder resonators. Such resonators are capable of trapping light in circulating orbits by multiple total internal reflections from the periphery. Owing to their nanoscale size, the resonant modes in NWs become leaky and interact more effectively with the outside world, carrying out a valuable antenna function enhancing their performance. This effect is further enhanced by embedding the Ge detector in a metal–semiconductor–metal heterostructure. Consequently, intense research on studying thermally induced diffusion processes of metals into Ge NWs was carried out to fabricate reliable M-S-M heterostructures with reproducible contacts. In contrast to common metal–germanide formation, the Al–Ge exchange overcomes the difficulty in reproducibly and deterministically defining the stoichiometric phase as the stability of conventional NiGe–Ge nanojunctions is a key variability issue. Recently, the unconventional photo-excitation phenomenon of negative photoconductance (NPC), where the generated photocurrent being lower than the dark current, was reported in highly n-doped Ge NWs and was linked to charge carrier trapping. Moreover, in the quest to minimize dark currents, thus enhancing the performance of Ge photodetectors, concepts employing asymmetric contacts, self-powered operation, or operating the detector at the quantum ballistic limit were demonstrated. In this work, we follow a distinctive approach, where for the first time the transferred-electron effect in Ge is exploited, to enable negative differential resistance (NDR) driven dark current suppression. Based on the Ridley–Watkins–Hilsum theory, this transport mechanism is triggered by high electric fields forcing a scattering of electrons from the energetically
favorable conduction band valley, characterized by a low effective mass, to a heavy mass valley nearby. Consequently, operating the photodetector in the NDR valley region, the dark current of the photodetector can be significantly decreased.

RESULTS AND DISCUSSION

In this work, we demonstrate a highly sensitive Ge NW photodetector with switchable photoconductance, effective dark current suppression, and polarization sensitivity. The Ge-based photodetectors are based on nominally intrinsic VLS-grown Ge NWs with diameters of approximately 25 nm. The large surface to volume ratio of these NWs is significantly enhancing photogating due to the increased charge carrier trapping in thin Ge NWs. For surface passivation and enabling stable as well as reproducible measurements, the Ge NWs are enwrapped with a protective 20 nm thick Al2O3 shell. Next, the Ge NWs are transferred onto an oxidized highly p-doped Si substrate and contacted by Al pads. For metal−semiconductor heterostructure formation, a thermally induced exchange reaction between the NWs and Al contact pads was applied to achieve Ge segments contacted by quasi-1D single crystalline Al NWs with atomically sharp and flat heterojunctions (see Figure 1a). A false-color SEM image of an actual Al−Ge−Al NW heterostructure with a Ge channel length of $L_{\text{Ge}} = 250$ nm is shown in Figure 1b. Recently, the structural properties of Al−Ge−Al NW heterostructures were analyzed by high-resolution transmission electron microscopy (HR-TEM) and energy dispersive X-ray spectroscopy, provided in the work of Kral et al. and El Hajraoui et al.

To probe the dark-characteristic of our Al−Ge−Al-based photodetector, we applied a bias to the highly p-doped Si substrate, thus, operating the device as a back-gated field-effect transistor (FET). The transfer characteristic shown in Figure 1c reveals an $I_{\text{ON}}/I_{\text{OFF}}$ ratio of approximately $10^4$ and a slight ambipolar behavior. Importantly, due to the large surface-to-volume ratio of thin NWs, adsorbates and (trapped) surface charges have significant impact on the electrical characteristics. For such Ge NWs, interface trap densities of $D_t \approx 10^{13}$ eV$^{-1}$ cm$^{-2}$ were shown, up to 3 orders of magnitude higher compared to planar Ge structures. Considering the Ge NW device shown in Figure 1c, roughly $n = 4000$ traps (see Supporting Information) are involved determining the device behavior. In this respect, it was shown that electrostatic gating can be effectively utilized to control the surface trap population and thus surface doping effects.

Upon laser illumination, the threshold voltage ($V_{\text{th}}$) shifts by approximately 2 V, which we link to the photogating effect. As schematically depicted in the inset of Figure 1b: photons impinging on the Ge detector (1) promote the generation of hot electrons (2), which efficiently fill high energetic traps acting as negative local gate (3), increasing the photo-conductive gain.

The high photoconductivity in Ge NWs is related to the trapping of photogenerated electrons into energy states at the favorable conduction band valley, characterized by a low effective mass, to a heavy mass valley nearby. Consequently, operating the photodetector in the NDR valley region, the dark current of the photodetector can be significantly decreased.

Figure 1. (a) Schematic illustration of the Al−Ge−Al NW heterostructure photodetector embedded in a back-gated FET architecture and false-color SEM image of an Al−Ge−Al NW heterostructure with a channel length of $L_{\text{Ge}} = 250$ nm. (b) Transfer characteristic of the Ge-based photodetector with (black) and without (red) laser excitation. The inset is showing a schematic illustration of the trap-assisted NPC in Ge, including (1) the excitation, (2) the generation of hot carriers, and (3) the trapping of excited electrons. (c) Time-dependent response of $I_D$ for a Ge NW device exposed to a long laser pulse. The observed photocurrent can be split into a fast and a slow component.

3470
semiconductor—insulator interface. The trapping dynamics is slow with time constants up to several minutes. To investigate this effect, a 4 min long laser pulse at a wavelength of $\lambda = 532$ nm was applied on a Ge NW and the response of $I_D$ was monitored over time. The measurement results are shown in Figure 1c for a device with $L_{Ge} = 500$ nm.

A superposition of two different contributions to the photocurrent can be identified. The component with time scales below 1 s is referred as $I_{ph,slow}$. In contrast, $I_{ph,fast}$ occurs at time scales reaching up to several minutes. It is believed that the slow increase of current under illumination corresponds to the filling of interface traps. Illumination with photons of energies well above the bandgap generates hot electrons in the conduction band. Such electrons are high-energetic and therefore can occupy empty surface states at the interface or even in the surrounding oxide high-k dielectric, where they act as a local negative gate. This in return, drastically increases the number of holes in the channel and therefore the conductivity. Macroscopically, this effect corresponds to a photogenerated shift of the threshold voltage to higher positive values and is referred to as photogating. Although similar time constants are observed for electrostatic gating of the device, one major difference can be spotted in the results. The filling of traps is now significantly faster, even though the depletion takes approximately the same time as before. This is attributed to the presence of high-energetic electrons, which are able to fill interface traps more efficiently. The illumination with light is therefore a possibility to accelerate charge trapping in Ge NWs. The origin of $I_{ph,fast}$ is more complicated. Besides the two above-mentioned mechanisms, a third effect can contribute to the fast increase of current under illumination. A large part of charge carriers generated due to the internal photoelectric effect can be extracted directly at the contacts without being trapped in the process. However, as the photoconductive gain of this mechanism is limited to one, its influence on the obtained results is negligible. In Ge NWs, $I_{ph,fast}$ is highly dependent on the effective gating. Thus, it is believed that charges trapped into faster interface traps contribute to the PV effect as well. Hence, a combination of both mechanisms is observed in the conducted measurements.

Importantly, the ambipolar nature of the Al–Ge–Al-based Ge photodetector allows to switch between hole and electron conduction. While for $V_{BG} < 10$ V, a positive photoconductance (PPC) is visible, operating the Ge photodetector at $V_{BG} > 10$ V, a pronounced NPC is observable.

Recently, we have systematically investigated the electron transport in Al–Ge–Al NW transistors, revealing the unambiguous observation of NDR (see Figure S1). Respective $I/V$ measurements recorded by linearly increasing $V_D$ are shown in Figure 2. A linear representation of the data revealing the dramatic current drop due to the valley region of the NDR is shown in the upper inset. In this configuration, hot electrons are scattered from the energetically favorable conduction band valley, characterized by a low effective mass to a heavy mass valley nearby. Consequently, as schematically illustrated in the lower inset of Figure 2, the transferred electron effect in Ge is attributed to apply between the L-point and X-point minima of the conduction band with the respective effective masses of $m^*_{Lz} = 0.082m_0$ and $m^*_{Xz} = 0.288m_0$. While NDR was observed in devices with $L_{Ge}$ between 150 to 900 nm, longer Ge channels increase the device resistance, shifting the NDR region to higher voltages (see Figure S2). Consequently, devices with $L_{Ge} = 500$ nm were investigated, as they provided the best compromise considering the performance metrics of NDR such as the peak-to-valley ratio and the span of the valley region (see Figure S3). For such a device, the valley of the NDR characteristic can be effectively used for dark current ($I_{dark}$) suppression by a factor of 100 compared to the non-NDR regime ($V_{BG} = 5$ V vs 30 V).

Figure 3 shows the Ge photodetector operated in the NDR regime ($V_{BG} = 30$ V). Upon excitation with a laser wavelength of $\lambda = 532$ nm, not only an effective suppression $I_{dark}$ in the valley region, but also a bias-switchable PPC and NPC is observable. This tunable photoconductivity is achieved by...
photodetector devices with the exciting light intensity. Additional measurements of Ge with responsivity was determined to be current density, rephotodetector is signifi-

measurements (see Figure S4). To further characterize the bias reproducibility and appeared to be stable for consecutive NDR dark-current characteristics showed a remarkable weakening for excitation with higher light intensities, while the PPC is increasing. Figure S5 shows the PPC and NPC versus illumination density, (i.e., the number of measured electrons per incident photon) for the NPC and PPC are $I_{\text{NPC}} = -1.7 \times 10^5$ and $I_{\text{PPC}} = 4.4 \times 10^5$, respectively. The wavelength-dependent gain of both the PPC and NPC is shown in Figure S9. While both the bias-switchable PPC/NPC with relative symmetric responsivity and the high gain of our Ge NW-based detector are advantageous, we want to stress that detectors based on trap-assisted mechanisms, such as photogating, are intrinsically slow and are limited by their charge carrier trapping and detrapping dynamics.

Consequently, for potential future applications, the measurement cyclability and endurance needs to be improved. This could be realized by a measurement setup including a steering circuit that delivers a repeating sequence of voltage pulses for the detrapping of charge carriers between measurements and therefore allows to continuously “reset” the device prior to the measurement of photocurrent.

Further, the insets of Figure 3 are showing the relative change in current $\Delta I_{\text{ph}}(\%) = \left( I_{\text{ph}} - I_{\text{dark}} \right) \times 100$ based on the evaluation of the spectral response of the NPC at $V_D = 1.25$ V and the PPC at $V_D = 4$ V in the wavelength range between $\lambda = 700$ and 1600 nm.

In agreement with the wavelength-dependent light absorption efficiency calculated for Ge NWs based on the Lorenz-Mie theory for light scattering, $^{13}$ the PPC reveals a peak $\Delta I_{\text{ph}}$ at $\lambda = 500$ nm,$^{14}$ while in the near-infrared between $\lambda = 800$ and 1200 nm a relatively constant $\Delta I_{\text{ph}}$ is observed. Interestingly, an even broader region between $\lambda = 500$ and 1300 nm with constant $\Delta I_{\text{ph}}$ is observed for the NPC. For both the PPC and NPC, $\Delta I_{\text{ph}}$ decreases for $\lambda > 1300$ nm, which is related to inefficient generation of electron–hole pairs for approaching the direct bandgap transition of Ge at the Gamma point ($E_G = 0.8$ eV). Most notably, the relatively wide bandwidth of the proposed Ge photodetectors makes them potentially attractive for wavelength-division multiplexing.$^{14}$

Figure 4. (a) Semilogarithmic $I/V$ characteristic recorded for a back-gate voltage of $V_{BG} = 30$ V without illumination (black) and for laser excitation at $\lambda = 532$ nm with a light intensity of $P = 0.3$ W/cm$^2$ for changing the polarization of the laser light incident on the Ge photodetector according to the schematic in the inset. (b) Thereof evaluated angle-dependent photocurrent for both PPC (red) and NPC (blue) in polar representation.
To probe the polarization sensitivity of the Ge photodetector, Figure 4a shows photocurrent measurements carried out under $\lambda = 532 \text{ nm}$ illumination for changing the polarization of the incident light. A polar representation of the angle-dependent normalized photocurrent in the NPC and PPC region is shown in Figure 4b. Rotating the polarization from parallel excitation (TM mode, $0^\circ$) to perpendicular excitation (TE mode, $90^\circ$), the TM/TE ratio of the NPC at $V_D = 1.25 \text{ V}$ calculates to only 0.6, which is related to the high dark current in the peak-region of the NDR and the effective NPC under illumination. In contrast, the PPC reveals a pronounced polarization anisotropy with TM excitation, generating a significantly higher photocurrent than TE excitation. This effect can be attributed to the dielectric permittivity mismatch effect of the NW with its surroundings. The thereof calculated TM/TE ratio at $V_D = 4 \text{ V}$ is 33. This extremely pronounced polarization sensitivity can be explained by the charge carrier trapping dynamics at high dark current in the peak-region of the NDR and the effective NPC under illumination. In particular, the PPC reveals a remarkably high polarization sensitivity. Further, diameter-dependent calculations of the absorption with respect of the polarization revealed a strongly enhanced TM/TE ratio for thin Ge NWs as only the fundamental TM$_{01}$ leaky mode resonance supported.

The high TM/TE ratio of the PPC in the valley region of the NDR regime reveals the huge potential of our Al–Ge–Al NW heterostructure devices for polarization sensitive photodetectors.

## CONCLUSIONS

In conclusion, we report on a bias switchable PPC/NPC in the visible and near-infrared spectrum embedding an intrinsic Ge NW in an Al–Ge-based metal–semiconductor heterostructure and exploiting the NDR regime. An efficient dark current suppression by approximately a factor of 100 was achieved by operating the device in the NDR regime. The responsivity at $\lambda = 532 \text{ nm}$ and $P = 0.3 \text{ W/cm}^2$ was calculated to be $-75 \text{ kA/W}$ for the NPC ($V_D = 1.5 \text{ V}$) and $89 \text{ kA/W}$ for PPC ($V_D = 4 \text{ V}$). The photoconductive gains are $g_{\text{NPC}} = -1.7 \times 10^3$ and $g_{\text{PPC}} = 4.4 \times 10^4$, respectively. Most notably, both the PPC and NPC revealed a relatively wide bandwidth, suggesting that our Ge photodetectors are potentially attractive for wavelength-division multiplexing. Investigating the polarization sensitivity revealed a remarkably strong polarization anisotropy for the PPC with a TM/TE ratio of 33. Without losing its validity, the presented bottom-up Ge NW technology could be transferred to a top-down Ge on insulator technology providing a high compatibility with CMOS processing. The observed results may pave the way for optoelectronic applications of Ge NWs involving high integration densities, compact light tunable memory devices, highly resolved imaging, or light effect transistors.

## EXPERIMENTAL SECTION AND METHODS

### Device Fabrication.

The starting materials were Ge NWs with diameters of approximately 25 nm grown on a Si (111) substrate using the VLS process with germane (GeH$_4$, 2% diluted in He) as precursor and a 2 nm thick sputtered Al layer as a growth-promoting catalyst. The growth was performed in a low pressure hot wall CVD chamber. Subsequent to the growth, the Ge NWs were coated with 20 nm high-k Al$_2$O$_3$, using atomic layer deposition. The passivated Ge NWs were drop-cast onto a 100 nm thick thermally grown SiO$_2$ layer atop of a 500 nm thick highly p-doped Si substrate. Al contacts to the Ge NWs were fabricated by a combination of electron beam lithography, 22 s of BHF (7:1) etching, and 5 s HI (30%) etching to remove the Al$_2$O$_3$-shell as well as the native Ge oxide shell at the contact area, 100 nm Al sputter deposition, and lift-off techniques. A successive thermally induced exchange reaction by rapid thermal annealing at a temperature of $T = 624 \text{ K}$ in forming-gas atmosphere initiates the substitution of Ge by Al. Facilitating this heterostructure formation scheme allows the integration of single-crystalline monolithic Al–Ge–Al NW heterostructures with tunable channel lengths.

### Electrical and Optical Characterization.

The biasing of the proposed Al–Ge–Al NW heterostructures was performed using a Keysight B1500A semiconductor analyzer. For optical excitation, a frequency doubled Nd:YAG laser emitting linearly polarized light at $\lambda = 532 \text{ nm}$ was coupled into a WITec Alpha300 and focused on the device through a Linos 4× objective (NA = 0.1, WD = 5 mm) enabling a diffraction limited spot size of $\sim 6.5 \mu\text{m}$. The spectral response of the Ge photodetector was measured using the white light from a broadband laser source coupled to acoustic-optical tunable filters (AOTFs). The system consists of three AOTFs, acting as monochromators with separated channels for visible ($\lambda = 500–700 \text{ nm}$), near-infrared ($\lambda = 600–1100 \text{ nm}$), and infrared ($\lambda = 1100–2000 \text{ nm}$) light. The output from the AOTFs is coupled into a WITec Alpha300. The beam is passing a 50–50 beam splitter and is focused on the sample through a Linos 4× objective (NA = 0.1, WD = 5 mm).

### ASSOCIATED CONTENT

#### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsphotonics.1c01359.

Calculation of the number of surface traps in the Ge photodetector, additional 1/V measurements showing the reproducibility of NDR, dependence of the photoconductivity on the Ge detector length, dependence of the NPC and PPC vs light intensity, comparison of Ge-based photodetectors with respect to responsivity, detectivity, and wavelength-dependent gain of the proposed Ge photodetector device, bias-dependent responsivity of the Ge photodetector (PDF).

### AUTHOR INFORMATION

#### Corresponding Author

Walter M. Weber – Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria; orcid.org/0000-0001-9504-5671; Email: walter.weber@tuwien.ac.at

#### Authors

Masiar Sistani – Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria; orcid.org/0000-0001-5730-234X

Raphael Böckle – Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria

Maximilian G. Bartmann – Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria
Alois Lugstein – Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria; orcid.org/0000-0001-5693-4775

Complete contact information is available at: https://pubs.acs.org/10.1021/acsphotonics.1c01359

Author Contributions
*M.S. and R.B. contributed equally to this work. M.S. and M.G.B. performed the device fabrication. R.B. and M.S. conducted the electrical and optical measurements. M.S. wrote the manuscript. A.L. provided the Ge NWs. M.S., A.L., and W.M.W. conceived the project and contributed essentially to the experimental design. All authors analyzed the results and commented on manuscript.

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS
The authors thank the Center for Micro- and Nanostructures for providing the cleanroom facilities. The authors kindly acknowledge the coverage of open access costs by the TU Wien–Bibliothek.

■ REFERENCES
(24) Berger, P. R.; Ramesh, A. Negative Differential Resistance Devices and Circuits; Elsevier BV: Amsterdam, Netherlands, 2011.


