Strainoptronics:
A New Degree of Freedom for 2D Material Device Engineering

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Abstract *Here we introduce 'strainoptronics' – the local strain engineering of 2D materials for novel optoelectronic components. We exemplary demonstrate heterogeneously integrating 2D materials in photonic circuits thus realizing a photodetector featuring a strong photoresponse (responsivity 0.5 A W^{-1}) operating at 1,550 nm in silicon photonics.*

Introduction

The ever-increasing data demand of modern societies requires a more efficient conversion of data signals in the optical domain, from fiber optic internet to electronic devices, like a smartphone or laptop. This conversion process from optical to electrical signals is performed by a photodetector, a critical building block in optical networks. 2D materials have scientific and technologically relevant properties for photodetectors. Because of their strong optical absorption, designing a 2D material-based photodetector would enable an improved photo-conversion, and hence more efficient data transmission and telecommunications [1,2]. However, 2D semiconducting materials, such as those from the family of transition metal dichalcogenides, have, so far, been unable to operate efficiently at telecommunication wavelengths because of their large optical bandgap and low absorption [3].

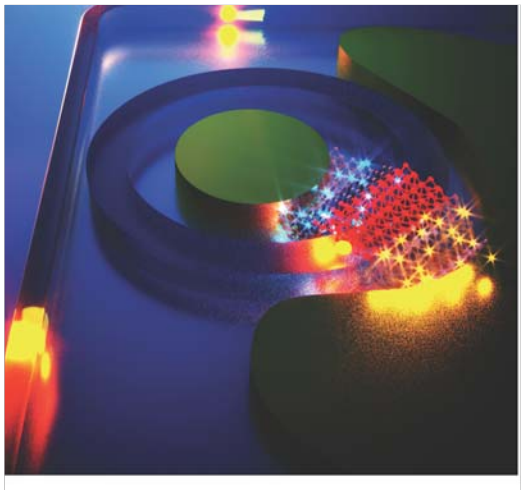


Fig. 1: The concept of Strainoptronics allows for mechanical tailoring of optical properties. 2D materials are especially suited in 2D materials. This image shows an artist rendering of wrapping a 2D material round a Silicon photonic waveguide to induce a bandgap shift and hence enabling C-band efficient photodetector.

Results

Strainoptronics provides a solution to this shortcoming and adds an engineering tool for researchers to modify the electrical and optical properties of 2D materials, and thus the pioneered 2D material-based photodetectors (**Fig. 1**).

Realizing the potential of strainoptronics, we stretched an ultrathin layer of molybdenum telluride, a 2D material semiconductor, on top of a silicon photonic waveguide to assemble a novel photodetector, and used their newly created strainoptronics "control knob" to alter its physical properties to shrink the electronic bandgap, allowing the device to operate at near infrared wavelengths, namely at the telecommunication (C-band) relevant wavelength around 1550 nm [4].

One interesting aspect of this work is, that the amount of strain these semiconductor 2D materials can bear is significantly higher when compared to bulk materials for a given amount of strain. We note that these novel 2D material-bas re sensitive compared to other photodetectors using graphene. Photodetectors capable of such extreme sensitivity are useful not only for data communication applications but also for medical sensing and possibly even quantum information systems. In integrated photonics, specific wavelengths such as 1,550 nm are preferred due to low-loss transmission and the availability of optical gain in this spectral region. For chip-based photodetectors, two-dimensional materials bear scientifically and technologically relevant properties such as electrostatic tunability and strong light–matter interactions. However, no efficient photodetector in the telecommunication C-band has been realized with two-dimensional transition metal dichalcogenide materials due to their large optical bandgaps. Here we demonstrate a $MoTe_2$-based photodetector featuring a strong photoresponse (responsivity

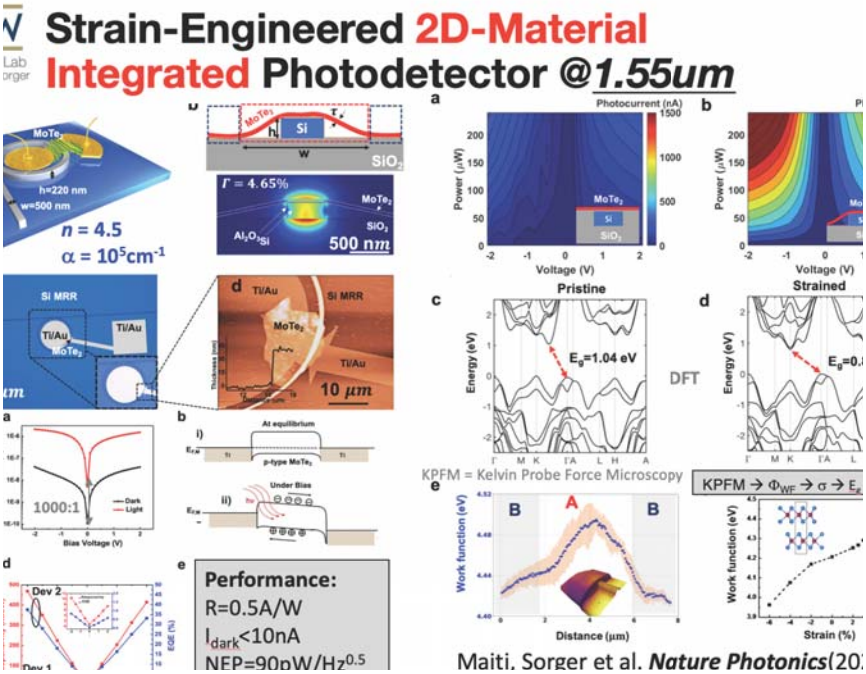
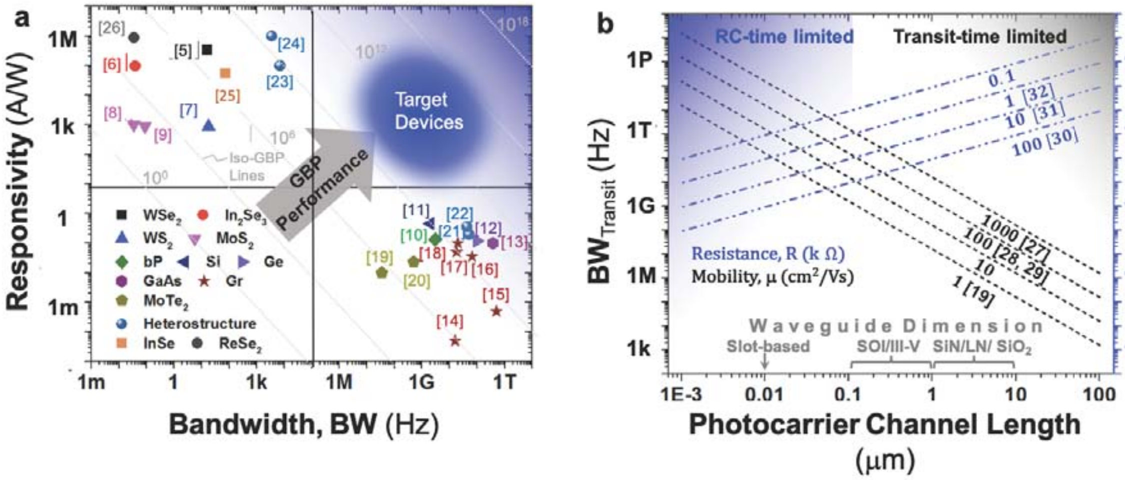


Fig. 2: 2D Material strainoptronics engineered Photodetector in Si-PIC [4]. **Top-left**: device design wrapping a MoTe2 around a Si waveguide. **Bottom-left:** Device performance showing a responsivity of 0.5 A/W at 1550 nm wavelength enabled by strain engineering the bandgap. **Right: a,** unstrained control devices show no significant photocurrent, unlike **b**, strained devices (experimental data binned). **c-f**, support measurements of Kelvin probe force microscopy (KPFM) and DFT resulting in an ~3% local strain of this device reducing the bandgap from (intrinsic) $MoTe_2$ 1.04eV to (strained) 0.80 eV, this

0.5 AW^{-1}) operating at 1,550 nm in silicon photonics enabled by strain engineering the two-dimensional material (**Fig. 2**) [4]. Non-planarized waveguide structures show a bandgap modulation of 0.2 eV, resulting in a large photoresponse in an otherwise photoinactive medium when unstrained. Unlike graphene-based photodetectors that rely on a gapless band structure, this photodetector shows an approximately 100-fold reduction in dark current, enabling an efficient noise-equivalent power of 90 $pW/Hz^{0.5}$. Such a strain-engineered integrated photodetector provides new opportunities for integrated optoelectronic systems.

Building on this 2D material detector demonstration and on the concept of strainoptronics, we recently investigated a roadmap towards achieving a high gain-bandwidth-product photodetectors exploiting the high absorption of 2D materials, photonic waveguides, and plasmonics slot waveguides [5].

Photodetectors are key optoelectronic building blocks performing the essential optical-to-electrical signal conversion, and unlike solar cells, operate at a specific wavelength and at high signal or sensory speeds. Towards achieving high detector performance, device physics, however, places a fundamental limit of the achievable detector sensitivity, such as responsivity and gain, when simultaneously aimed to increasing the detector's temporal response, speed, known as the gain-bandwidth product (GBP). While detector's GBP has been increasing in recent years, the average GBP is still relatively modest (~10^6-10^9 Hz-A/W). Here we discuss photoconductor-based detector performance limits and opportunities based on arguments from scaling length theory relating photocarrier channel length, mobility, electrical resistance with optical waveguide mode constrains. We show that short-channel detectors are synergistic with slot-waveguide approaches, and when combined, offer a high-degree of detector design synergy especially for the class of nanometer-thin materials. Indeed, we find that two-dimensional material-based detectors are neither limited by their low mobility nor by associated carrier velocity saturation limitations and can, in principle, allow for 100 GHz fast response rates, which is unlike traditional detector designs that are based on wide channel lengths. However, contact resistance is still a challenge for such thin photo absorbing materials – a research topic that is still not addressed yet. An interim solution is to utilize heterojunction approaches for functionality separation. Nonetheless, atomistic and nanometer-thin materials used in such next-



performance cluster into two quadrants; high responsivity yet low speed (bandwidth, BW), and vice versa. Target detectors with a GBP of ~10^{12} - 10^{13} scale orthogonally (upper-right quadrant) to the iso-GBP lines. b) Plot of bandwidth vs. photocarrier-collecting electrical channel length showing two regimes where the transit time-limited bandwidth ($BW_{transit}$) is dominant for long-channel detectors (gray shade), whereas for sub 100 nm channel lengths, the bandwidth is limited by RC time (blue shade). $BW_{transit}$ is estimated for four different mobility values (1 - 1000 cm^2/Vs) for a V_{sd} = 1V]. The RC time-limited bandwidth (BW_{RC}) is estimated for four different resistance values starting from 0.1-100kΩ where, the electrical capacitance is determined by a parallel-plate model (fringe fields ignored) for a lateral junction. A finding of this parametric study is that for a (arbitrarily selected) target speed of 100 GHz; i) micrometer long channel-based photodetectors required a rather high mobility (<10^4 cm^2/Vs) but with a somewhat relaxed contact resistance RC requirements, yet high mobilities challenges achievable resistance due to scattering events induced by higher doping, while ii) 10's nm short-channel detectors are only resistance limited, since (near) ballistic transport is given even for poor mobilities (<10 cm^2/Vs), and relatively high grain can be achieved by reducing the transit time to ~ps as supposed to increasing the carrier lifetime. Such short-channel performance-detectors, however, demand optical mode squeezing to adhere to device *scale-length theory* (SLT) rules which can be achieved with slot-waveguide designs.

generation scaling length theory based detectors also demand high material quality and monolithic integration strategies into photonic circuits including foundry-near processes. As it stands, this letter aims to guide the community if achieving the next generation photodetectors aiming for a performance target of GBP ~ 10^{12} Hz-A/W.

Conclusions

Here we introduce the strainoptronics – a new degree of freedom to engineer optoelectronic devices. We demonstrate a strain-induced absorption-enhanced 2D nanocrystal ($MoTe_2$)-based silicon photonic microring-integrated photodetector featuring high responsivity of 0.01 A W–1 (device 1) and ~0.5 A W^{-1} (device 2) at 1,550 nm, with a low NEP of 90 pW/$Hz^{0.5}$. Subject to mechanical strain, the bandgap shifts towards 0.80 eV for strained $MoTe_2$, when the 2D nanocrystal is wrapped around a non-planarized silicon waveguide. The local enhancement of the work function mapped out by KPFM corresponds to a local change of strain of ~3 ± 1% according to DFT calculations. The device responsivity can be further improved using a high-quality-factor (Q) cavity resonator. We observe a 3 dB bandwidth of 35 MHz, where the response time is transit time limited. This strain-engineered bandgap enables optical absorption at 1,550 nm, resulting in an integrated photonic detector that could potentially open up a new pathway for future on-chip photonic circuits

Acknowledgements

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