Optically-Active Semiconducting Asymmetric Nano-Channel Diodes

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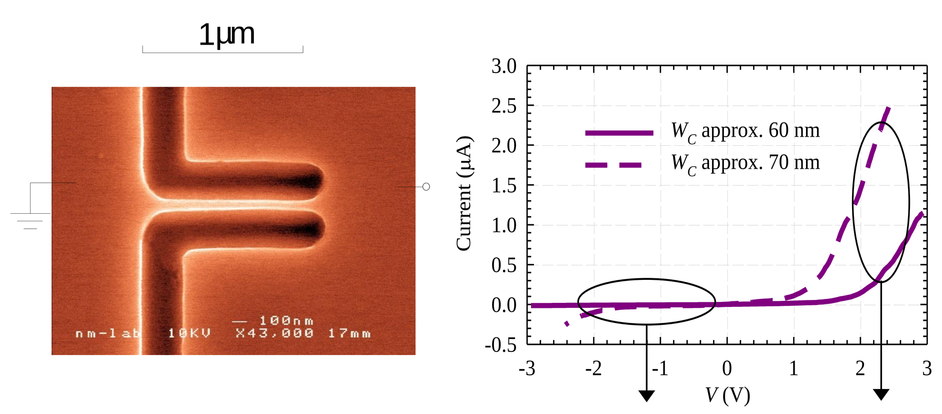
Our Project

We present our research on fabrication and optical characterization of novel, nanostructured semiconducting asymmetric nano-channel diodes (ANCDs). The ANCD [also called self-switching diode (SSD)] is fundamentally a new type of semiconductor nanodevice. Contrary to conventional diodes, the ANCD develops its nonlinear current-voltage (*I-V*) curve without barriers, relying instead on the asymmetry of the fabricated structure and field-controlled ballistic transport in a 2-dimensional electron gas (2DEG) channel of nanometer-width [1]. Based on Monte Carlo simulations, ANCDs are expected to be powerful, tunable THz generators [2], and, have been most recently demonstrated, to be sensitive THz detectors [3].

Here we demonstrate that ANCDs could be operated as very sensitive, single-photon–level, visible-light photodetectors.

Working Concept of ANCD



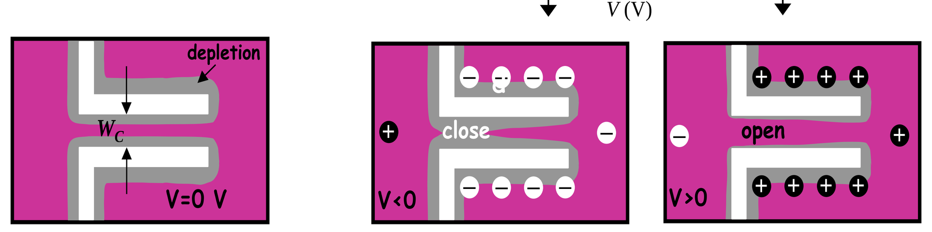


Figure (a) Figure (b) Figure (c)

IDEAL ANCDs

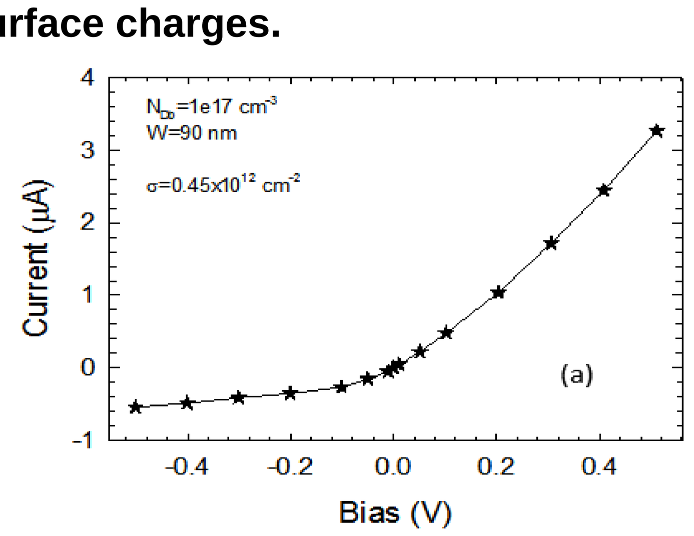
The 2DEG III-V layer with mobility of ~10,000 cm²/V.s acts as a *n*-type conducting channel connecting the two regions of the device.

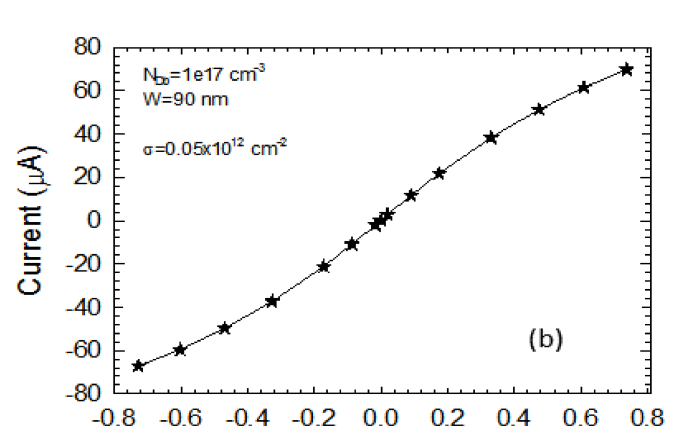
The final *I-V* characteristics of an ideal ANCD is diode-like.

At $V = 0$ in figure (a), the channel is almost pinched off by the native depletion regions (surface states–grey areas). The positive voltage applied to the right electrode in figure (c) lowers the depletion resulting in a large current. The negative voltage applied to the right electrode in figure (b) increases the depletion, pinching off the channel, resulting in minimal current.

REAL ANCDs

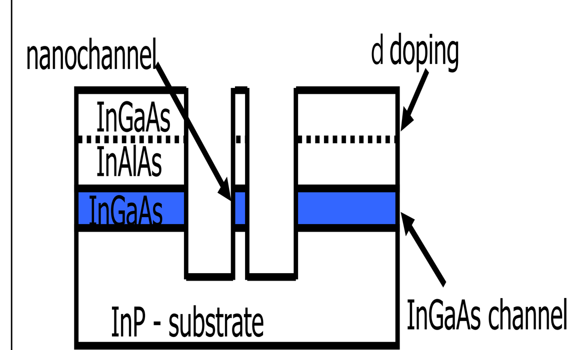
Depending on the fabrication process and the level of its control, ANC structures can exhibit quite different *I-V* characteristics. Below we show MC simulations of two ANCDs of the same geometry, but with different values of surface charges.

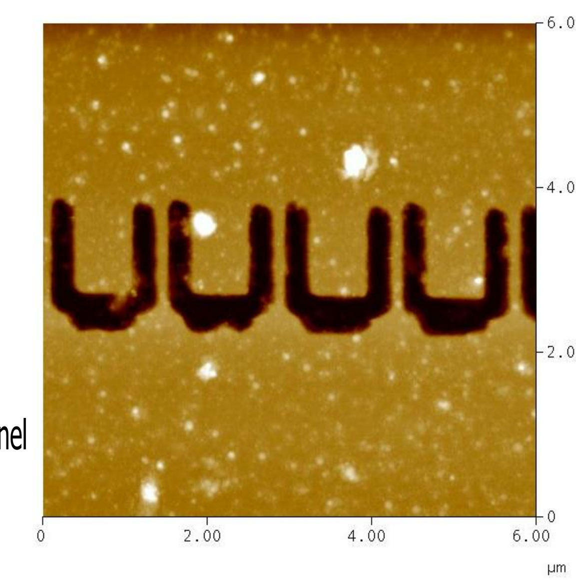




The *I-V* curve simulated for an ANCD with high σ at the channel (left panel) is highly nonlinear with a diode-like shape and resembles the ideal one shown above. The ANCD modeled for low σ has an S-like *I-V* shape with the channel conducting at the zero bias. The S-shape *I-V*'s are also typical of ANCDs with wide channels and their resultant nonlinearity comes from the Γ–L intervalley transition rather than asymmetric lateral gating.

Sample Fabrication





InGaAs/InAlAs Material Structure

$In_{53}Ga_{47}As$	10 nm
$In_{52}Al_{48}As$	5 nm
N+ DD Si	6.0e18
$In_{52}Al_{48}As$	10 nm
$In_{53}Ga_{47}As$	15 nm
$In_{52}Al_{48}As$	300 nm
Substrate	InP

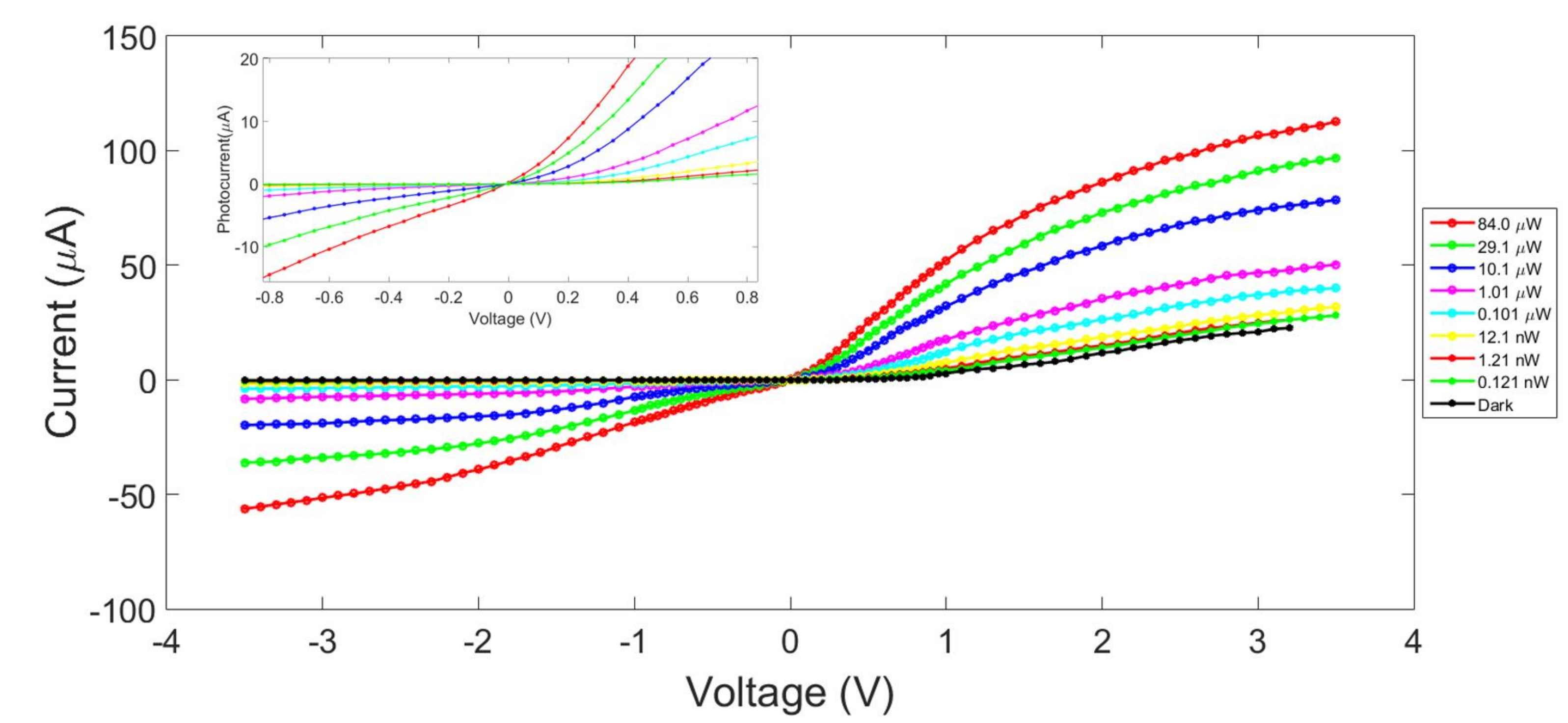
2DEG

Our test devices were fabricated on an InGaAs/InAlAs quantum-well heterostructure grown onto an InP wafer. The fabrication started with the formation of mesa structures via wet chemical etching using a $H_3PO_4/H_2O_2/H_2O$-based solution. Ohmic contacts were then formed via thermal evaporation of 50 nm Au/Ge/Ni alloy, followed by a 200 nm Au layer. The actual ANCDs under test exhibited a (1.5-μm-long by 286-nm-wide) channel fabricated using electron-beam lithography and wet chemical etching.

DC Photoresponse Measurements

As optical excitation, we used 800-nm quasi-continuous-wave radiation generated by a commercial Ti:sapphire laser.

Photoresponse of a device with diode-like *I-V* characteristics:



The observed behavior very strongly points to optical gating of the nano-channel. In fact, the first quadrant of the top-left inset graph (positive voltage and positive photocurrent) closely resembles the characteristics of a FET. FET I-V plots are usually dependent on various gate voltages, however here they correspond to different intensities of optical excitation. In a regular FET, the minimum gate voltage, which starts to affect the channel current is the threshold voltage, however, in our case, we have a threshold optical power.

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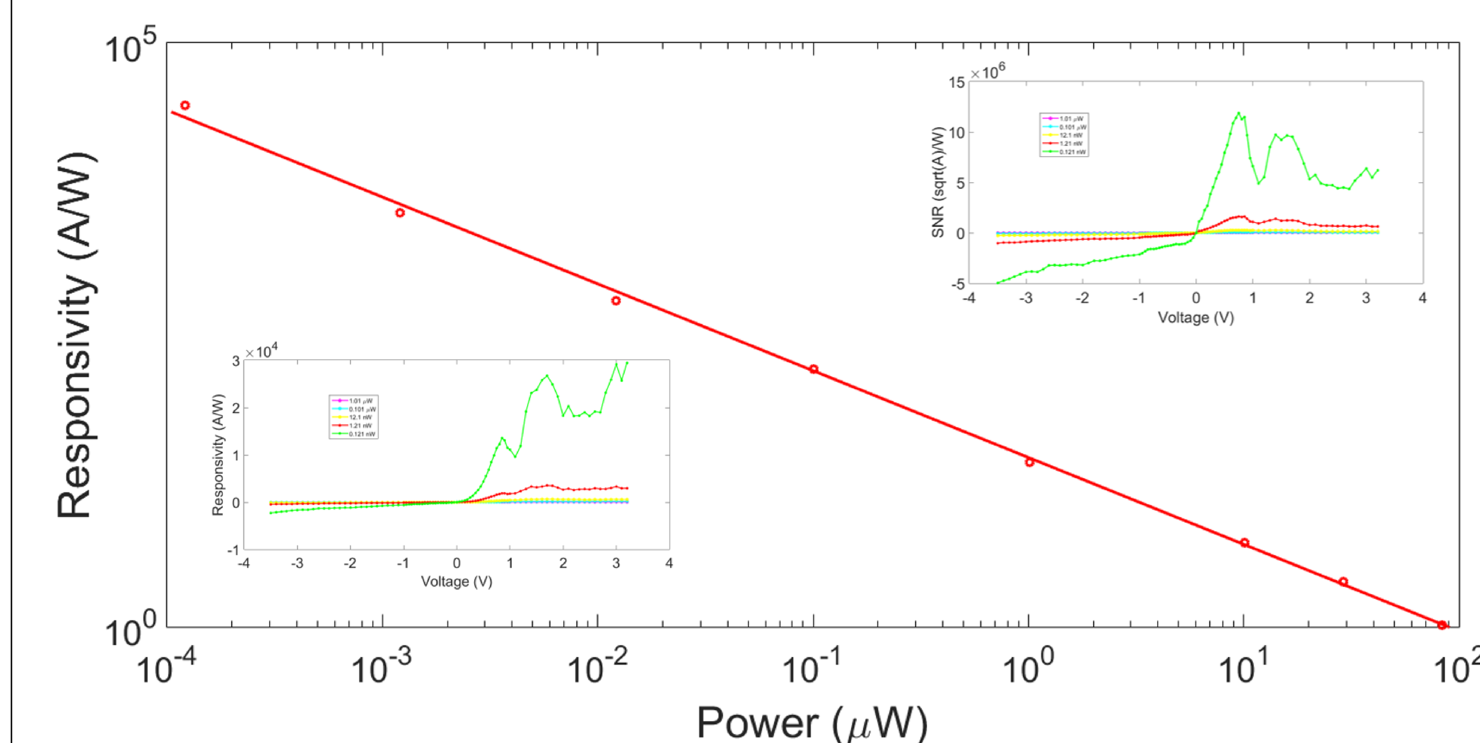
Photoresponse of a device with S-like *I-V* characteristics:



Here the unbiased ANCD is clearly in the ON state and when biased, the current is in the mA rather than μA range (see *I-V* curves in the right-top inset). The observed large nonlinearity comes from the Γ–L electron scattering. It is striking that optical responsivity, expressed in V/W shown in the left-bottom panel, increases with decreasing optical power. In fact, as it is shown in the main panel, it increases at the same rate of increase with decreasing power over many orders of magnitude with only very slight deviations, reaching the value of almost 100,000, comparable to the gain of avalanche-type, single photon detectors.

Existence of optical gain in this case is consistent with a model proposed for photoconductive gain in High Electron Mobility Transistors [4]. The band bending present in the 2DEG captures photo-excited electrons that transit the nano-channel, while photo-excited holes are pushed away from the 2DEG and become trapped in the substrate or in surface states on the sidewalls of the channel. The value of the photoconductive gain is the ratio of the hole trapping time to the electron transit time.

Conclusion

- We have demonstrated optical photoresponse properties of novel ANC nanodevices, originally intended for THz radiation generation and detection.
- For 800-nm wavelength excitation, we observed two-type of responses, optical gating and photoconductive gain, depending on the physical origin of the *I-V* curve nonlinearity of the studied ANCD.
- In both cases, ANCDs are very promising for photon detector applications.
- When cooled (to minimize the dark current) our ANC nanostructures should become practical photon counters. ANCDs implemented in InAS or InSB material systems are especially attractive since they will cover the telecommunication and thermal imaging wavelengths.
- Monte Carlo simulations seem to qualitatively reproduce the observed ANCD photoresponse behavior.

References:
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[4] M. A. Romero *et al.*, IEEE Trans. MTT 44, 2279 (1996).