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14. ABSTRACT

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Ultrahigh responsivity of optically active, semiconducting asymmetric nano-channel diodes

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Abstract. We present our research on the fabrication and optical characterization of novel semiconducting asymmetric nano-channel diodes (ANCDs). We focus on optical properties of ANCDs and demonstrate that they can be operated as very sensitive, single-photon–level, visible-light photodetectors. Our test devices consisted of 1.2-µm-long, ~200- to 300-nm-wide channels that were etched in an InGaAs/InAlAs quantum-well heterostructure with a two-dimensional electron gas layer. The ANCD I–V curves were collected by measuring the transport current both in the dark and under 800-nm-wavelength, continuous-wave–light laser illumination. In all of our devices, the impact of the light illumination was very clear, and there was a substantial photocurrent, even for incident optical power as low as 1 nW. The magnitude of the optical responsivity in ANCDs with the conducting nano-channel increased linearly with a decrease in optical power over many orders of magnitude, reaching a value of almost 10,000 A/W at 1-nW excitation.

1. Introduction

Room-temperature nano-devices based on quantum confinement and/or ballistic nonlinearities are intrinsic nanostructures, not simply scaled-down conventional circuitry, and are gaining wide-spread research attention. Among the nano-devices, one of most popular are the asymmetric nano-channel diodes (ANCDs), also referred to as self-switching diodes (SSD), first proposed by Song *et al.* [1]. ANCDs, contrary to conventional diodes, do not rely on energy-barrier concepts to achieve rectification, but rather their nonlinear I–V characteristics result from the carrier transport in an asymmetric nano-channel. The ANCD planar geometry allows for a flexible design and easy integration as a multi-element sensor or with either optical nano-concentrators or THz coupling antennas. Based on Monte Carlo (MC) simulations, ANCDs are expected to be efficient THz generators [2], which have been demonstrated to be viable THz detectors [3].

Typically, carrier transport in ANCDs is confined to a two-dimensional electron gas (2DEG) layer in order to take advantage of the 2DEG ultrahigh mobility and in this way, minimize the carrier transient time. Depending on the device's dimensions and/or fabrication process and the level of its control, there are two basic types of SSDs: "normally OFF" devices with a channel open/depleted at zero bias and "normally ON" devices, where the channel is always conducting. These two types exhibit quite different I–V curves, as shown in figures 1(a) and 1(b), where MC simulations [4] of two ANCDs of the same geometry are presented but with different values for the surface charge σ.

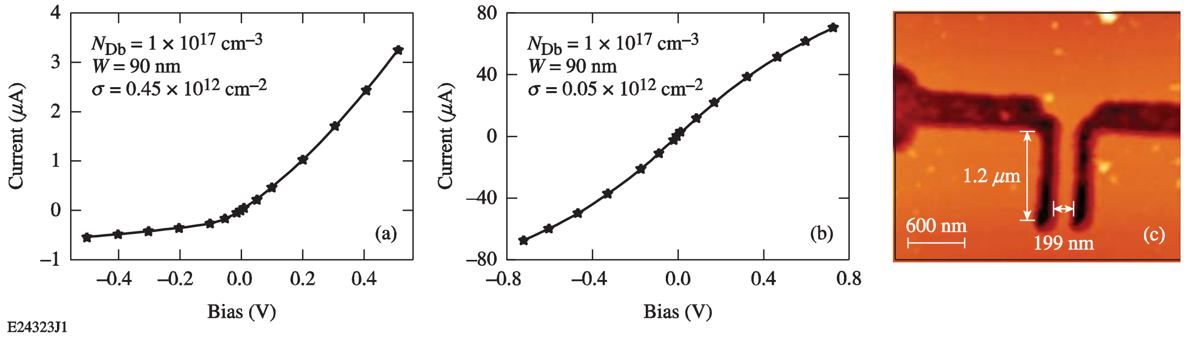

Figure 1. Monte Carlo (MC) results for I–V curves of an asymmetric nano-channel diode (ANCD) with a channel width $W = 90$ nm and two different values of the surface charge σ, leading to (a) a depleted channel and diode-like characteristics, (b) a conducting channel (effective width of 80 nm at zero dc bias) and nonlinear characteristics, and (c) an atomic force microscope image of an actual device.

Despite the popularity of SSDs, extensive fundamental and applied research is still needed to fully understand their carrier transport dynamics through the asymmetric nano-channel, as well as their performance in both the THz and optical radiation ranges. Our work presented here focuses on photoresponse properties of ANCDs, and we demonstrate that especially normally ON devices possess a very strong, intrinsic internal photoelectron gain mechanism, making them attractive as possible ultrafast optical detectors with single-photon sensitivity.

2. Device fabrication and experimentation

Our tested devices consisted of ~1.2-µm-long and ~200- to 300-nm-wide channels [see figure 1(c)] and were fabricated on an InGaAs/InAlAs quantum-well heterostructure grown on an InP wafer. The fabrication started with the formation of mesa structures by wet chemical etching with an $H_3PO_4/H_2O_2/H_2O$-based solution. Ohmic contacts were then formed by thermal evaporation of 50 nm of Au/Ge/Ni alloy, followed by a 200-nm Au layer. Finally a nano-channel was defined using electron-beam lithography and wet chemical etching.

The ANCD I–V curves were collected by measuring the transport current for the voltage-source biasing condition, both in the dark and under light illumination. For optical excitation, we used 800-nm-wavelength continuous-wave (cw) radiation generated by a commercial, non-mode-locked Ti:sapphire laser.

3. Experimental results and analysis

Figure 2 presents a family of dc I–V characteristics of a normally OFF device, measured in the dark (black dots) and with a single-µW level of light illumination (see figure caption) focused on the device. We note that the curve measured in the dark resembles well the one presented in figure 1(a). The unbiased ANCD is clearly in the OFF state and, when biased, a diode-like characteristic is well reproduced. A leakage current at negative bias is ascribed to the relatively large channel width of this ANCD sample, while the change of the slope near 3-V bias is caused, according to MC simulations, by velocity saturation associated with electron scattering from Γ into L satellite valley.

The impact of the light illumination is very strong, as it is illustrated in the top left inset in figure 2, where we plot a family of photocurrent characteristics versus the bias voltage. The observed behaviour very strongly points to optical gating of the nano-channel. In fact, the first quadrant (positive voltage and positive photocurrent) of the inset graph closely resembles the characteristics of a field-effect transistor (FET), except that here the various curves of the graph correspond to different optical intensities with a threshold optical power of about 0.9 µW. Optical gating in FETs has been recently studied [5]; however, here we have a much simpler structure—an asymmetric nano-channel—and the effect is very strong, even as the incident light power changes in a very narrow range from 1 to 1.4 µW.

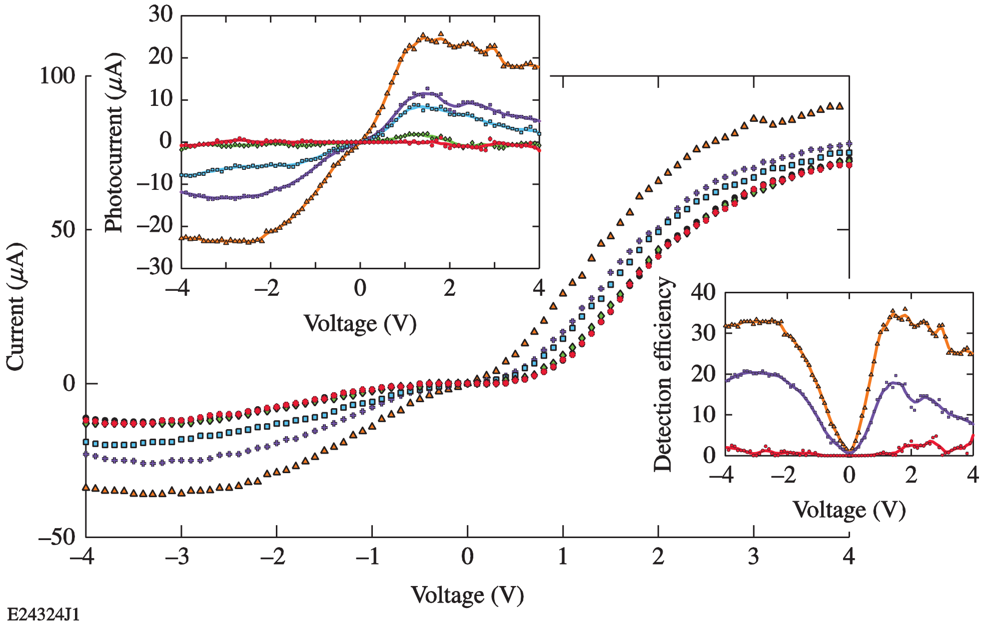

Figure 2. Direct current I–V characteristics for a normally OFF device (channel width of ~200 nm) in darkness (black dots) and under 800-nm-wavelength cw laser illumination. The top left inset shows the photocurrent's dependence on the bias voltage, collected as the current difference between the I–V curve under a given illumination and the one measured in the dark. The bottom right inset presents the detection efficiency's (DE's) dependence on the bias voltage, calculated for a given curve as the ratio of the photocurrent to incident laser power and expressed in units of (electron/photon). The legend for all presented traces is as follows: yellow triangles 1.4 μW; violet crosses 1.27 μW; light blue squares 1.05 *m*W; green diamonds 0.91 μW; and red stars 0.78 μW.

The optical gating is caused by photogenerated holes that move to locations below and/or beside the channel and are likely to partly compensate negative surface charges at the walls of the trenches. This effect reduces the channel depletion in the analogous way to a gate voltage in the FET, further opening the 2DEG channel and, consequently, leading to a large optical responsivity. The latter conclusion is in full agreement with the detection efficiency (DE) data presented in the bottom right inset in figure 2. The DE value increases with the incident light power and the ANCD structure exhibits an intrinsic gain, i.e., a DE >> 1 resulting from the optical gating of the channel of the SSD.

A family of I–V characteristics, this time collected for a normally ON device, is shown in the top right inset in figure 3 and was measured under light illumination conditions similar to those in figure 2. We note that now the I–V curve measured in the dark (black dots) has an S-like shape and resembles the one presented in figure 1(b). The unbiased diode is clearly in the ON state, and when biased, the current is in the mA rather than the μA range. The observed nonlinearity (transition toward saturation) comes, as indicated earlier, from the *Γ*–*L* electron scattering. Figure 3 (main panel) shows that the maximum optical responsivity (red dots), expressed in A/W (see also the left bottom panel), increases linearly (red solid line) with decreasing optical power over many orders of magnitude with only very slight tapering at the lowest light power levels, reaching a value of almost 10,000 A/W, comparable to the gain of avalanche-type, single-photon detectors.

Optical gain in normally ON ANCDs is consistent with a model proposed for photoconductive gain in high-electron-mobility transistors (HEMTs) [6]. In this model, the band bending present in the 2DEG of the HEMT captures photoexcited electrons, which transit the channel of the device, while photoexcited 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. The gain is dependent on the optical power because the density of photogenerated charges affects the potential (as in the case of the normally OFF device) that separates the photogenerated holes from the 2DEG, thereby affecting the hole trapping time. The subpicosecond electron transit time of our ANCDs translates into a very large optical gain.

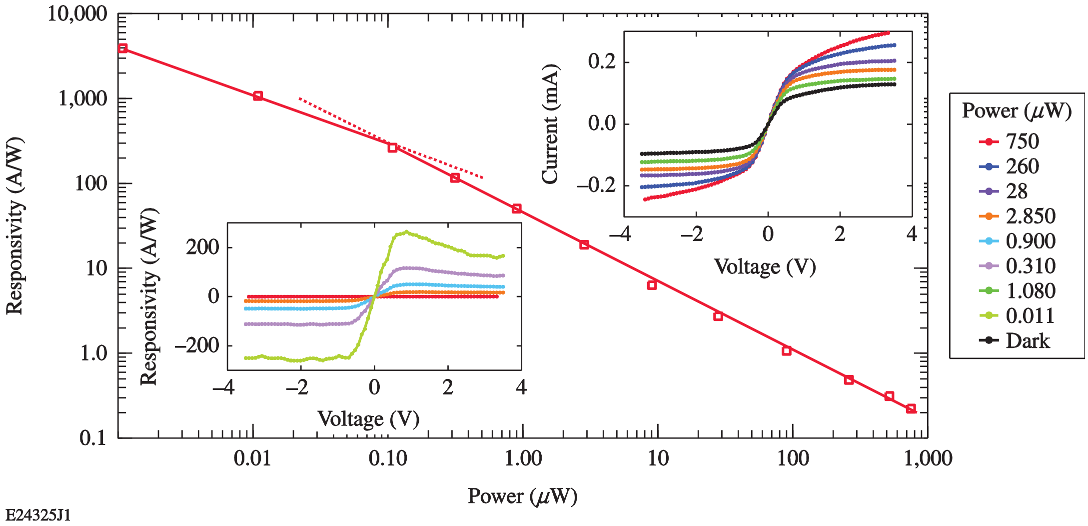

Figure 3. Maximum optical responsivity's (red dots; solid line is a linear fit) dependence on the incident optical power for a normally ON ANCD (channel width ~300 nm). The top right inset shows the I–V characteristics collected in the dark (black dots) and under 800-nm cw light illumination for power levels in the range of 750 to 0.11 μW. The bottom left inset presents examples of the responsivity versus the bias voltage.

4. Conclusions

We have shown that ANCDs, originally intended for THz applications, have also very interesting photoresponse properties. In normally OFF devices, where the nano-channel width is defined by the depletion layers and electric-field–controlled, optical illumination plays a role in optical gating, analogous to the gate in FET structures. On the other hand, the physics of the photoresponse gain mechanism in normally ON ANCDs arises from a dramatic difference between a subpicosecond transient time of electrons travelling in the 2DEG nano-channel layer and the microsecond lifetime of holes, optically excited and, subsequently, pushed toward the substrate. When cooled (to minimize the dark current), our ANCDs should be practical photon counters.

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