Influence of the In content and surface reconstruction on the properties of submonolayer quantum dot infrared photodetectors.

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1- Introduction and samples:

Submonolayer quantum dots (SML-QDs) have several advantages over conventional Stranski-Krastanov quantum dots (SK-QDs): more flexible size control, higher surface density, and the absence of a wetting layer. However, they suffer much more from the consequences of In segregation that reduces their In content and internal strain field. That, in turn, weakens the alignment of the small two-dimensional (2D) InAs islands that are the building blocks of those nanostructures. In this work, three infrared photodetectors based on SML-QDs (SML-QDIPs) with a similar basic structure (Fig. 1) were grown by molecular beam epitaxy (MBE). One of them, used as a reference (sample #A), had SML-QDs formed in a conventional way by repeating six times a basic cycle consisting of 0.5 monolayer (ML) of InAs followed by 2.5 MLs of GaAs. To increase the In content and local strain field as much as possible in the second device (sample #B), the GaAs interlayer was kept as thin as possible and the basic cycle (also repeated 6 times) was instead 0.3 ML of InAs followed by 0.7 ML of GaAs. Sample #C was identical to sample #A but was grown at higher temperature in order to get SML-QDs formed in the presence of a (2×4) reconstruction of the GaAs(001) surface that is supposed to provide better 2D InAs islands than the usual c(4×4) reconstruction [1]. After growth, the samples were processed into small 0.4×0.4 mm^2 mesas using photolithography, wet etching, and e-beam metallization. Then the devices were fixed on a chip carrier, wire bonded, and installed on the cold finger of an optical cryostat in order to check their optical and electrical properties at 12 K.

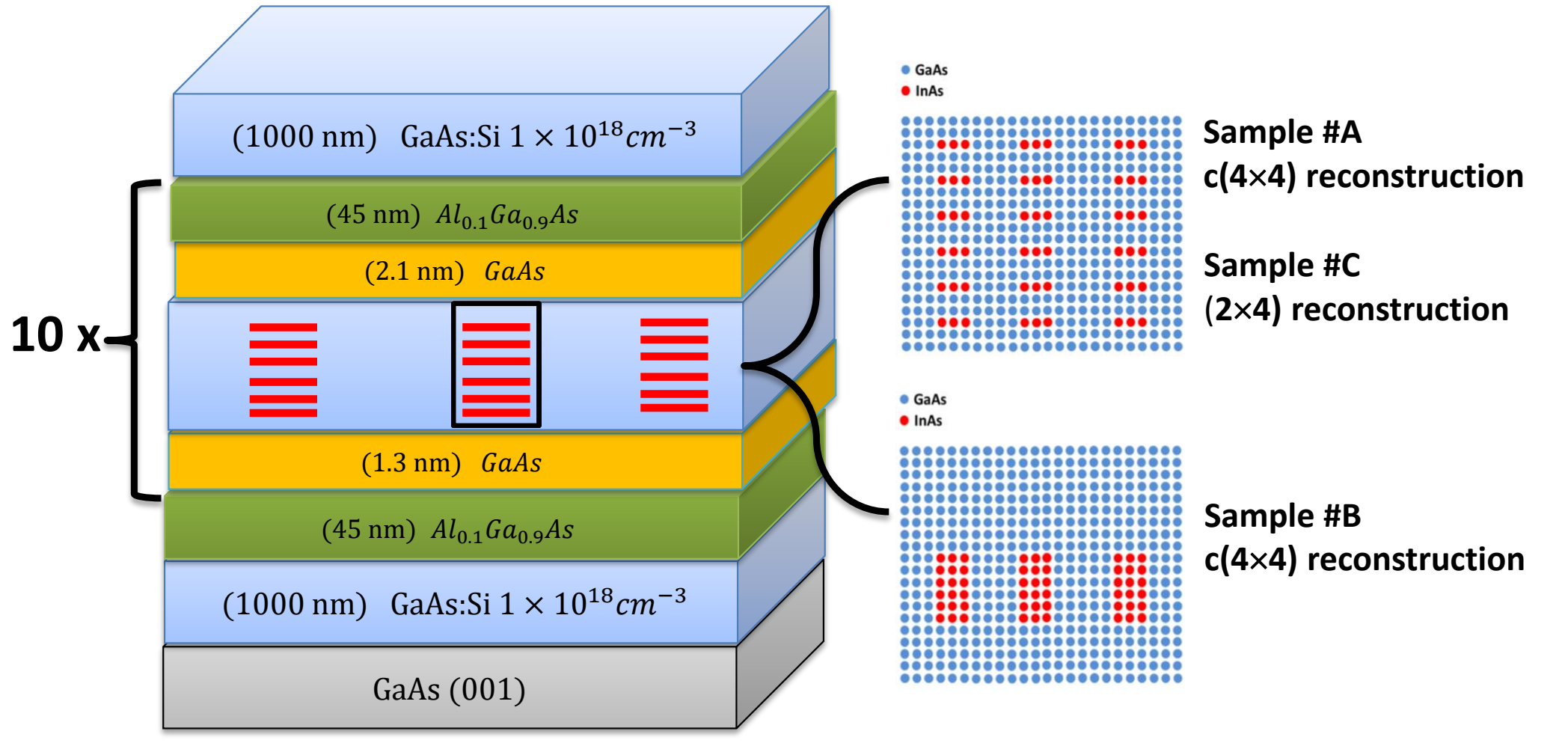

***Figure 1**: Structure of the SML-QDIPs showing the differences between samples #A, #B, and #C.*

2- Experimental results:

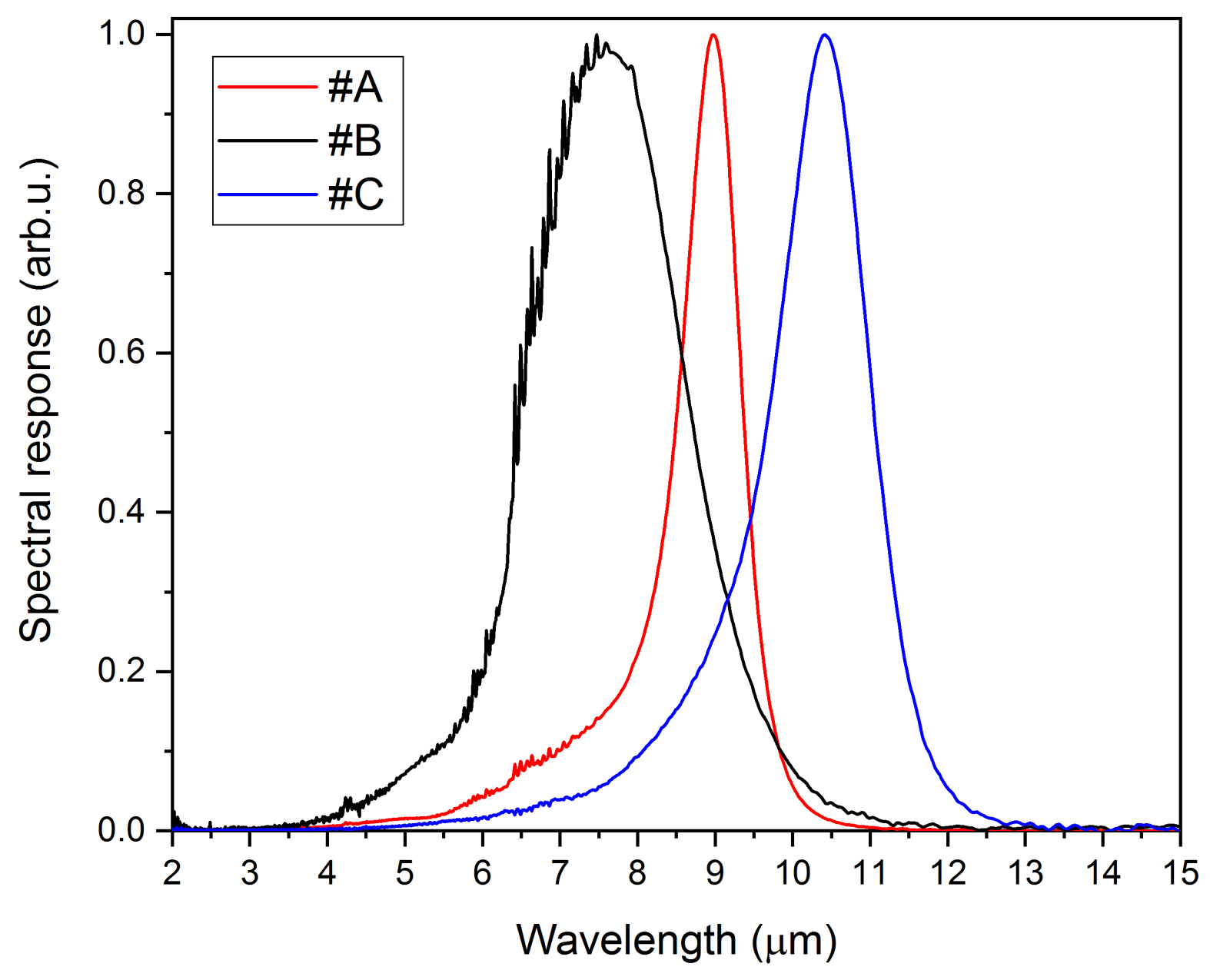

***Figure 2**: Normalized spectral response of the SML-QDIPs obtained by FTIR under normal incidence at 12K.*

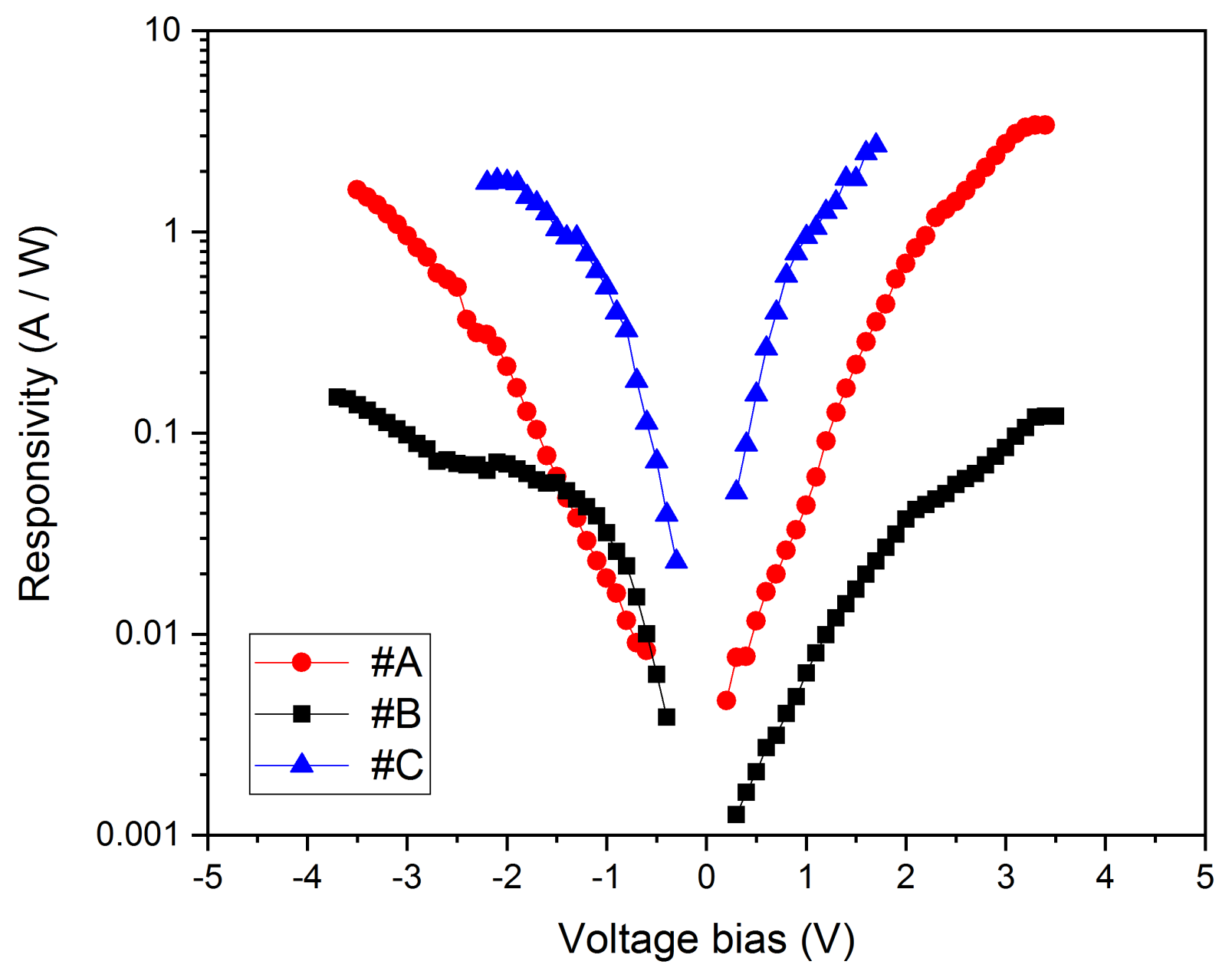

***Figure 3**: Black-body responsivity of the SML-QDIPs under normal incidence as a function of bias at 12K.*

The spectral response of the devices was measured by FTIR under normal incidence and is reported in Fig. 2. The absorption of sample #B is broader and blueshifted (λ_{max}=7.6 µm), when compared to sample #A (λ_{max}=8.9 µm). The broader peak is related to the stronger quantum effects due to the smaller size of those SML-QDs (6 ML high instead of 18 MLs), while the blueshift can be explained by the richer In content (nominally, 100% instead 33% in sample #A) that lowers the gap of the SML-QD material and therefore increases the transition energy from their ground state to the excited state of the $Al_{0.1}Ga_{0.9}As$/GaAs quantum well. This effect clearly overcomes the influence of their smaller size that should actually increase their confinement energy and, consequently, lower their transition energy. Sample #C has also a broader absorption, but it is redshifted (λ_{max}=10.4 µm) with respect to sample #A. Since it was grown at higher temperature, In segregation was stronger and probably slightly reduced the size and/or In content of those SML-QDs. A slightly stronger evaporation of the In atoms from the surface might also lead to the same results.

Fig.3 shows that the responsivity of sample #C is highest and the responsivity of sample #B is lowest, following the same trends as the intensity of the absorption curves shown in Fig. 2. It is worth mentioning here that the absolute doping of the SML-QDs was kept constant in all the samples and was originally adjusted for the density of SML-QDs in the reference device (sample #A), that was initially estimated to be around 4.5×10^{11} cm^{-2}. Since a lower In fraction (as in sample #B) is supposed to yield a larger density of SML-QDs (at least in the range used here) [1], the doping of that sample may no longer be optimum and could be responsible for its lower absorption and responsivity. As samples #A and #C had a more similar composition, size and density of their SML-QDs, the superiority of sample #C was probably related the (2×4) surface reconstruction used during formation of the nanostructures, as will be discussed later.

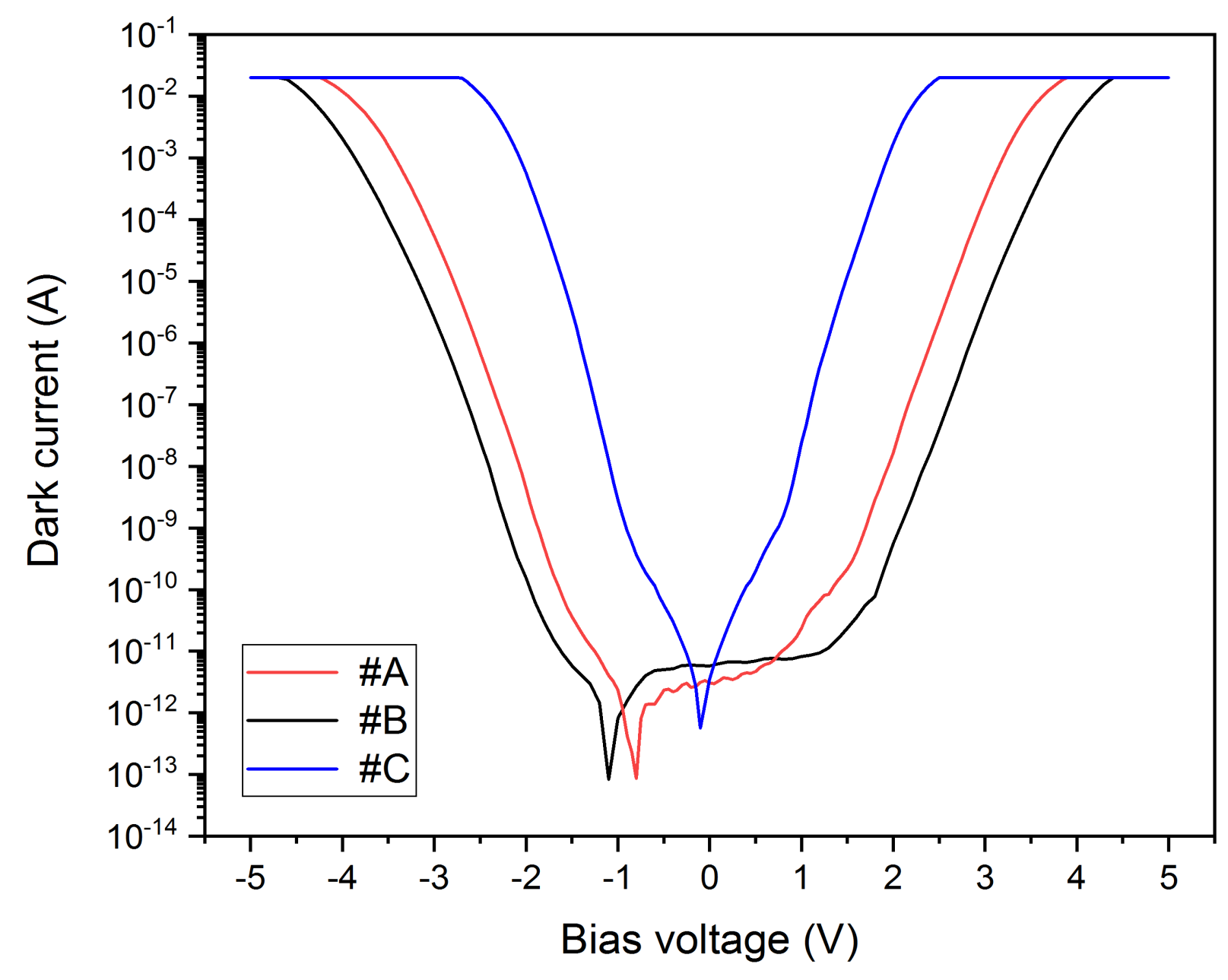

***Figure 4**: Dark current as a function of bias voltage at 12K.*

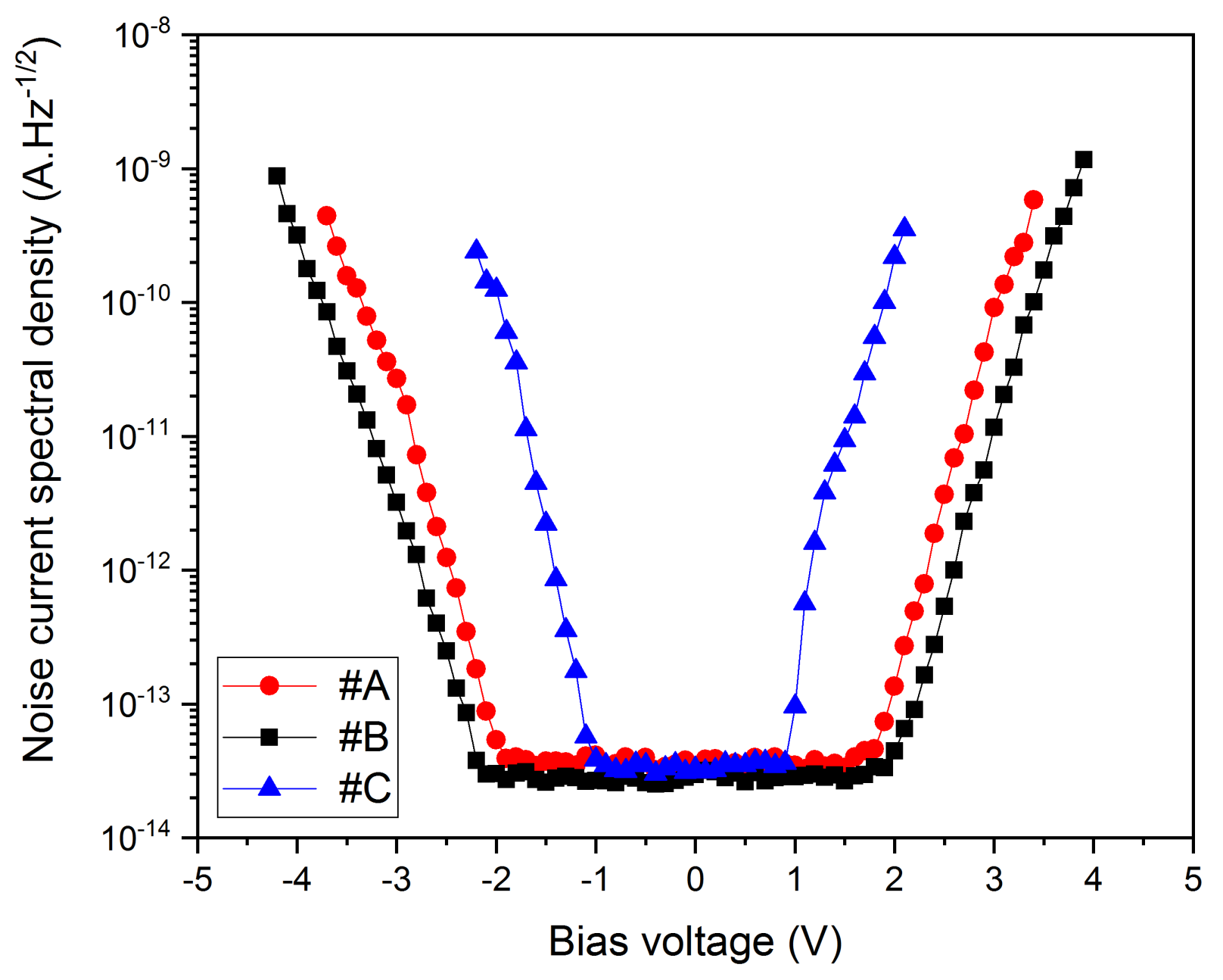

***Figure 5**: Noise spectral density of the dark current as a function of bias voltage at 12K.*

To perform the dark-current and noise measurements, the devices were surrounded by a copper shield that was in thermal equilibrium with the sample holder. Fig. 4 shows that the dark current of sample #C was always much larger than that of the other samples, which is consistent with the higher ground-state energy of those SML-QDs suggested in Fig. 2, leading thus to a smaller activation energy. At low bias, the narrow plateau observed in samples #A and #B is due to the intrinsic limitation of the experimental setup to measure lower currents, while, at higher bias, the exponential dependence of the current (linear dependence in a logarithmic scale) is related to field-assisted tunneling through the top of the $Al_{0.1}Ga_{0.9}As$ barriers that are distorted by the applied bias.

Since the main source of noise in a photoconductive photodetector is due to the generation-recombination noise from the dark current, one expects the noise curves (Fig. 5) to show the same trends as the dark current (Fig. 4). The plateau observed at low bias is due to the noise floor of the experimental setup that prevents any measurement below 4×10^{-14} A Hz$^{-1/2}$.

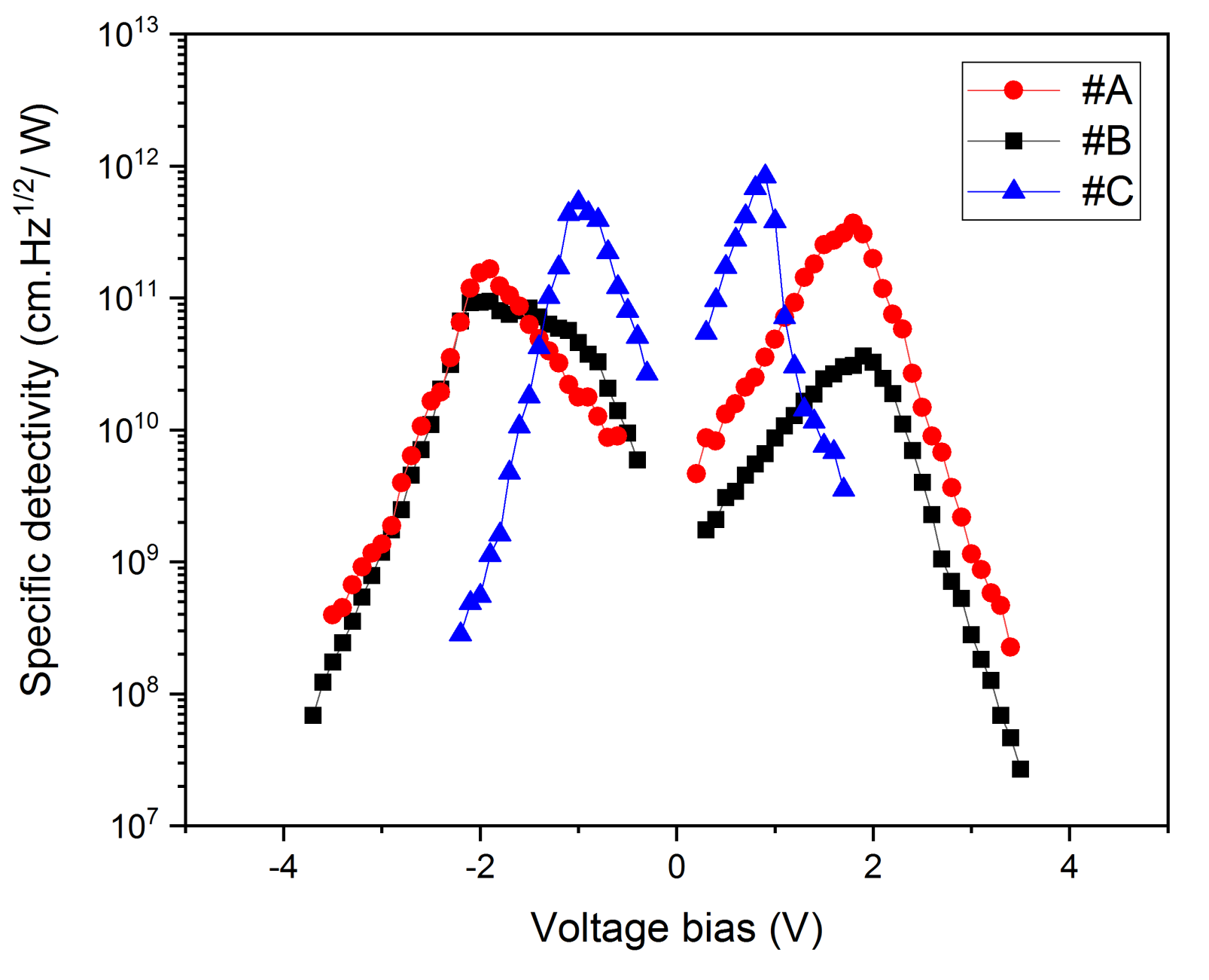

***Figure 6**: Specific detectivity of the SML-QDIPs at 12K.*

The specific detectivity is proportional to the ratio of the responsivity and noise-current spectral density and is shown in Fig. 6. Although the responsivity is a monotonic function of the bias, the detectivity curves have a maximum due to the steep increase of the noise beyond a certain bias voltage. The maximum values for sample #A, #B and #C are respectively 3.7×10^{11} cm Hz$^{1/2}$ W^{-1}, 9.4×10^{10} cm Hz$^{1/2}$ W^{-1}, and 8.3×10^{11} cm Hz$^{1/2}$ W^{-1}. Although there is no doubt that the usual growth conditions used for sample #A already provide SML-QDIPs with excellent optical properties, it seems that using a (2×4) surface reconstruction in sample #C yields an even better performance. It is probably be due to the fact that a c(4×4) reconstruction of the GaAs(001) surface prior to InAs deposition actually leads to the incorporation of individual In atoms into the deep trenches of the As-rich surface [2] – forming thus a random InGaAs alloy – while true 2D InAs islands can only be nucleated in the presence of a (2×4) reconstruction [1]. SML-QDs were already previously grown with a (2×4) reconstruction but using a lower sample temperature and a much lower As flux [3]. Such experimental parameters didn´t provide any improvement of the devices, as a consequence of the limited In incorporation under such As-poor conditions that also resulted in a lower SML-QD density [4].

3- Conclusion and references:

In this work, we grew, processed and tested 3 different SML-QDIPs and investigated two ways to increase further the In content of such nanostructures. Reducing the thickness of the GaAs spacer between the InAs submonolayers was effective in increasing their In content but led to a worse performance of the device due to the increase of SML-QDs density and the lack of adequate doping. An extra study of their doping would be necessary to check if this kind of structure is indeed promising. A much better performance was achieved when the SML-QDs were deposited at slightly higher temperature than usual, in the presence of a (2×4) surface reconstruction, that is supposed to be the only way to truely form small 2D InAs islands. Although the device had a specific detectivity among the highest ones ever reported at low temperature, the activation energy of its dark current was rather small, suggesting that its behavior at higher temperature might worsen considerably. As a consequence, it would require higher barriers or thin confinement layers to operate in better conditions.

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[2] DOI: https://doi.org/10.1016/S0039-6028(97)00355-5
[3] DOI: https://doi.org/10.1063/1.5125238
[4] DOI: https://doi.org/10.1103/PhysRevMaterials.4.114601

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