High-Speed InSb Photodetectors on GaAs for Mid-IR Applications

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***Abstract*—We report p-i-n type InSb-based high-speed photodetectors grown on GaAs substrate. Electrical and optical properties of photodetectors with active areas ranging from 7.06×10^{-6} cm^2 to 2.25×10^{-4} cm^2 measured at 77 K and room temperature. Detectors had high zero-bias differential resistances, and the differential resistance area product was 4.5 Ω cm^2. At 77 K, spectral measurements yielded high responsivity between 3 and 5 μm with the cutoff wavelength of 5.33 μm. The maximum responsivity for 80-μm diameter detectors was 1.00×10^5 V/W at 4.35 μm while the detectivity was 3.41×10^9 cm Hz$^{1/2}$/W. High-speed measurements were done at room temperature. An optical parametric oscillator was used to generate picosecond full-width at half-maximum pulses at 2.5 μm with the pump at 780 nm. 30-μm diameter photodetectors yielded 3-dB bandwidth of 8.5 GHz at 2.5 V bias.**

***Index Terms*—High-speed, infrared, photodetector.**

I. Introduction

InSb is an attractive material due to its potential use in infrared photodetectors like other narrow band-gap compound semiconductors. Infrared detectors can be used in thermal imaging systems, free-space communication, and chemical agent monitoring. Although variable-bandgap HgCdTe has been used for many years, it is being replaced by quantum well or InSb photodetectors due to the technological difficulties [1]. InSb is the common material for the midinfrared (mid-IR) range photodetectors with the cutoff wavelength of 5.4 μm at 77 K. Ternary compounds of InSb have been used with the addition of As, Bi, or Tl to extend the responsivity to the far infrared region [2], [3]. Although these detector structures can be fabricated on InSb, GaSb, or InAs substrates, this method is not preferred due to low resistance of the substrate and the difficulty of thinning process for the back-illuminated focal plane arrays [4]–[6]. Instead, Si and GaAs substrates are more attractive even if there is a significant lattice mismatch between the substrate and epitaxial layers [7]–[9]. Although optical and electrical properties have been studied over the years, high-speed properties of InSb-based photodetectors have not been reported before. In this paper, we report the high-speed operation of InSb photodetector in the mid-IR wavelengths. The electrical and spectral responsivity characteristics at 77 K are also reported.

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II. Design and Fabrication

The epitaxial structure was grown on semi-insulating GaAs substrate by molecular beam epitaxy. A 0.1-μm-thick GaSb buffer layer was grown before the growth of the InSb layers. The photodetector consisted of a 0.5-μm-thick p+ InSb layer at the top, 1.5-μm-thick intrinsic InSb layer, and a 1.5-μm-thick n+ InSb layer at the bottom. The intrinsic layer was unintentionally doped to 2×10^{15} cm^{-3}, while the highly doped layers were doped to 10^{18} cm^{-3}. N+ and p+ layers were doped with Tellurium and Beryllium, respectively.

The devices were fabricated by a microwave-compatible process and completed in five steps. A citric acid:H_2O_2 (1:1) solution was used to etch the InSb. Samples were patterned and etched down to the n+ InSb layer, which was followed by a self-aligned Ti–Au liftoff. The p+ ohmic contacts were also achieved by Ti–Au liftoff. Except for the active area, the layers were etched down to the n+ InSb layer. This was followed by the deposition of 0.5-μm-thick SiO_2 layer using plasma-enhanced chemical vapor deposition (PECVD) on the highly doped n+ layer. This layer was used as the insulating medium between the highly conductive InSb layer and the interconnect metal. The active area was covered with Si_3N_4 for passivation and isolation. The thickness of this layer was also chosen to form an anti-reflection coating. Finally, Ti–Au metal was evaporated to form the coplanar waveguide on top of the SiO_2 layer, which was essential for the high-speed operation.

Fig. 1 shows the cross section of a fabricated photodetector, while Fig. 2 shows the photograph of a 150-μm diameter active area photodetector after the fabrication.

III. Experimental Results

Current–voltage (I–V) characteristics of the photodetectors were measured at 77 K using a modular dc source/monitor unit. Photodetectors were biased between -2.0 and $+0.5$ V at 300 K background. The active area of the photodetectors ranged from 7.06×10^{-6} cm^2 (30 μm in diameter) to 2.25×10^{-4} cm^2 (150×150 μm^2). Fig. 3 shows the I–V characteristics of cooled photodetectors with 60-, 100-, and 150-μm diameter. The dark current of the photodetectors gradually increases with the increasing active area. Dark current at zero biases were 48, 118, and 239 nA for 60-, 100-, and 150-μm diameter photodetectors, respectively.

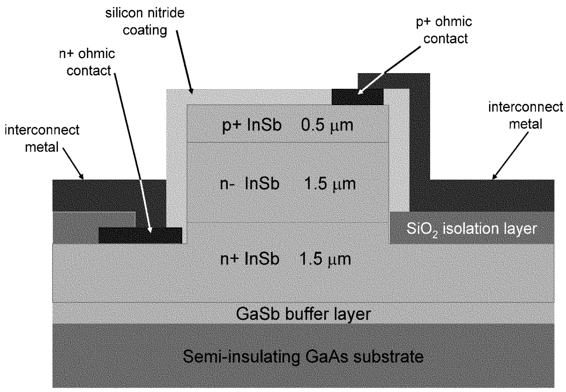

Fig. 1. Cross section of a fabricated photodetector.

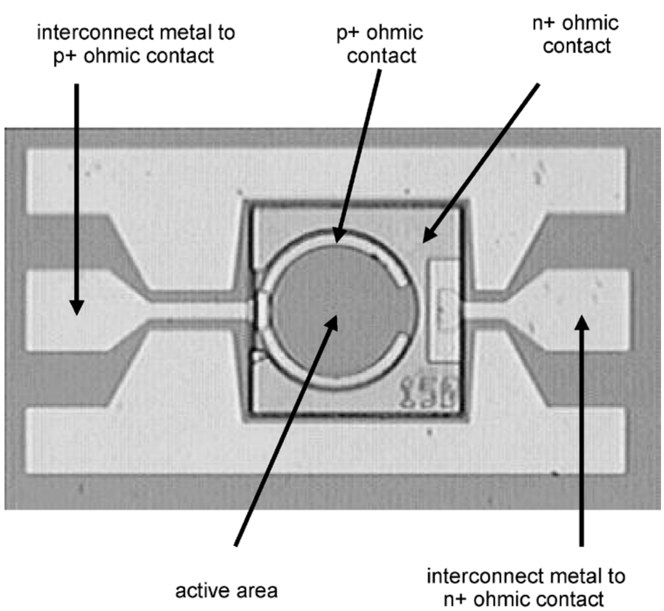

Fig. 2. Photograph of a photodetector with 150-μm diameter active area.

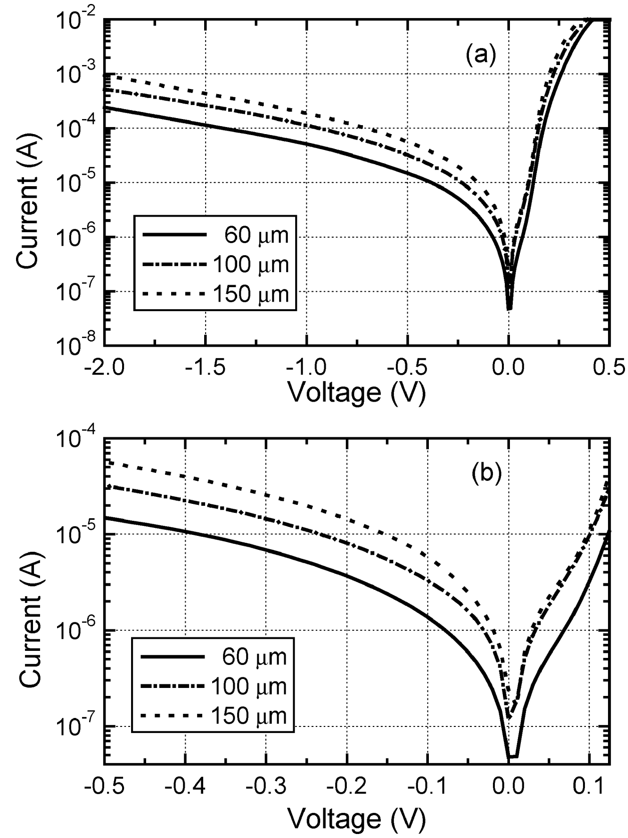

Fig. 3. (a) Measured current–voltage characteristics of 60-, 100-, and 150-μm diameter photodetectors at 77 K. (b) Detailed results around zero bias.

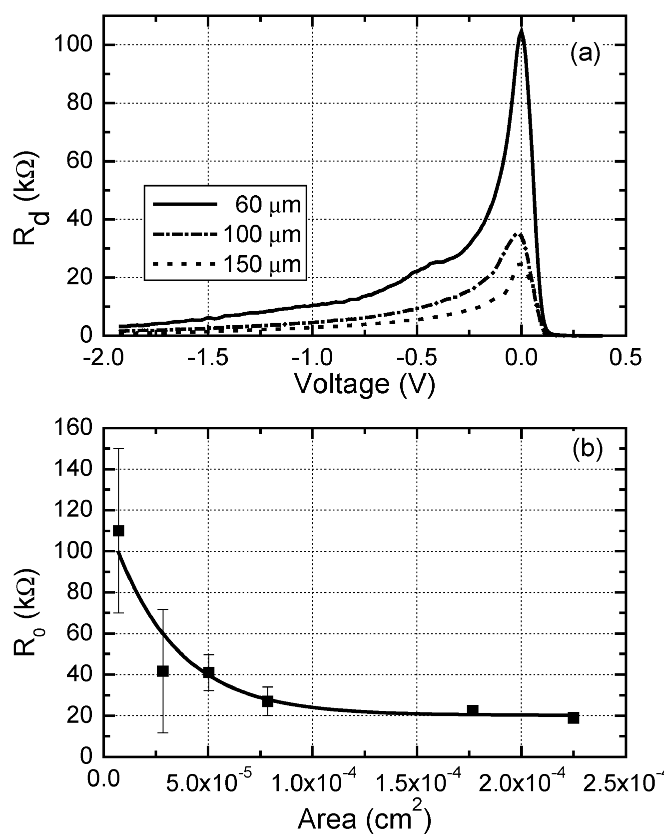

Fig. 4. (a) Calculated differential resistance $(\mathrm{R_d})$ as a function of bias voltage. (b) Zero bias differential resistance $(\mathrm{R_0})$ as a function of detector area.

We also calculated the differential resistances of the detectors. Our results are shown in Fig. 4(a). These results were calculated using the current–voltage values that were presented in Fig. 4. The peak position of the differential resistance shifted from -440 mV to 0 V with the decrease of the measurement temperature from 300 K to 77 K [9]. Fig. 4(b) shows the area dependence of the zero-bias differential resistance $(\mathrm{R_0})$. $\mathrm{R_0}$ had an exponential dependence on the active area. Resistance-area product $(\mathrm{R_0 A})$ for the largest area photodetectors was 4.5 Ω cm^2, while it was 7.8×10^{-1} Ω cm^2 for the smallest photodetectors. These values are comparable with the results of other InSb photodetectors grown on GaAs or Si substrates. Dark current density analysis as a function of area showed that the surface diffusion and generation current was dominant for low reverse bias values [10]. The $\mathrm{R_0 A}$ product was limited by these currents for small area detectors. A better passivation should be used or the temperature must be lowered to eliminate the surface currents.

The optical characteristics of the detectors were measured using a computer-controlled characterization system. Samples were mounted on an alumina substrate with thermally conductive epoxy. Electrical connections were made with wire

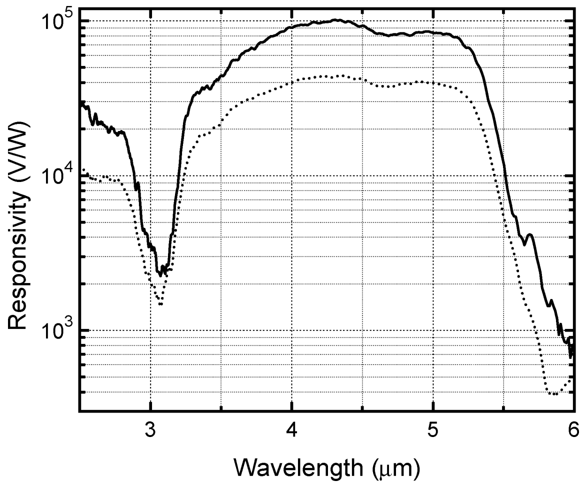

Fig. 5. Results of the spectral responsivity measurements are shown for 80- (solid line) and 60-μm (dotted line) diameter photodetector.

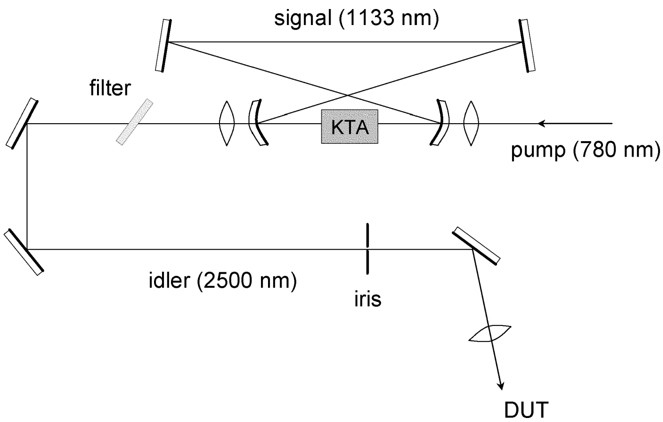

Fig. 6. Schematic diagram of the optical parametric oscillator.

bonding. A sample was placed in a dewar with ZnSe optical window for characterization. A blackbody at 774 K was used as the infrared (IR) light source. The detector signal and noise were measured using a low-noise preamplifier and a lock-in amplifier, while the IR light was chopped at 680 Hz. The spectral measurements were made in the 2.5- to 6.0-μm wavelength range using an Oriel MIR-8000 FTIR system and a pyroelectric reference detector. Fig. 5 shows the 77 K spectral response of 80- (solid line) and 60-μm (dotted line) diameter photodetectors. The cutoff wavelength (where the responsivity dropped to half of the maximum) was 5.33 μm. This corresponded to an energy bandgap of 0.23 eV, which was in good agreement with the theoretical value at 77 K.

Responsivity decreased sharply after the cutoff wavelength and it was two orders of magnitude below the maximum value at 6.0 μm. In the responsivity spectrum, two dips at 3.1 and 4.6 μm can be seen easily. This was due to the absorption peaks of ice in the IR region [11]. Due to leakage in the vacuum, water vapor accumulated on the detector, forming ice, which degraded the performance of the detectors. Maximum responsivities of the detectors were 1.00×10^5 V/W and 4.41×10^4 V/W, respectively at 4.35 μm. Both photodetectors had nearly equal current responsivity of 1.8 and 1.7 A/W, respectively, which corresponds to 49% quantum efficiency. We also measured high detectivities

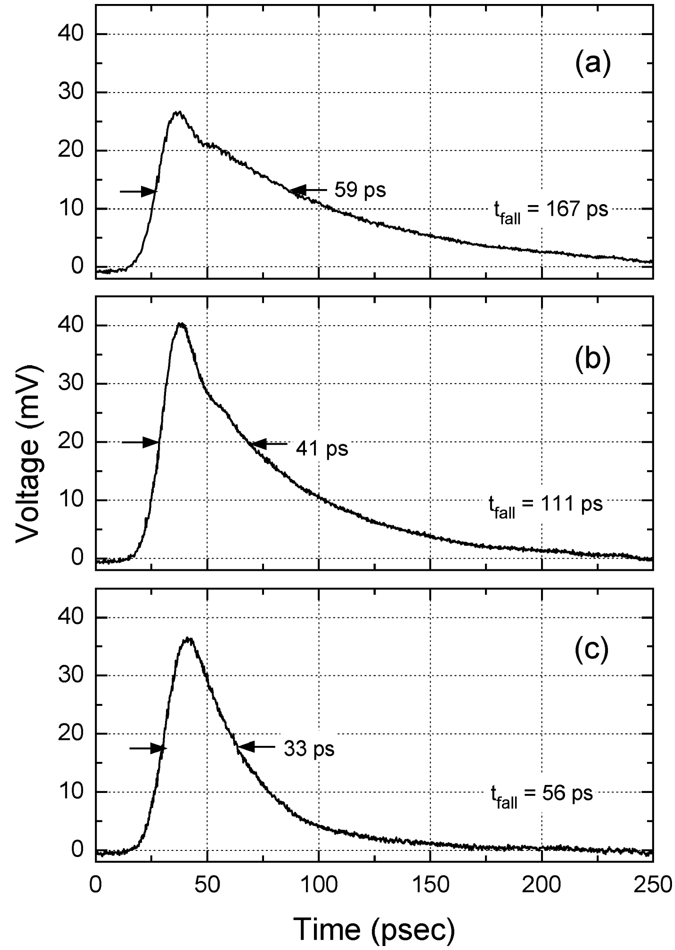

Fig. 7. Temporal response of a 30-μm diameter detector under (a) 0.5-, (b) 1.0-, and (c) 2.5-V bias.

for the photodetectors. Peak detectivities of the photodetectors were 3.41×10^9 cm $\mathrm{Hz}^{1/2}$/W for the 80-μm diameter detector and 7.98×10^9 cm $\mathrm{Hz}^{1/2}$/W for the 60-μm diameter detector.

Due to a lack of suitable measurement setup, high-speed measurements had to be done at room temperature. Picosecond full-width at half maximum (FWHM) pulses were generated using a $KTiOAsO_4$ (KTA)-based optical parametric oscillator (OPO) at 2500 nm. Fig. 6 shows the experimental setup of the OPO. The OPO consisted of an optical resonator with four mirrors that were highly reflective at the signal wavelength and a 20-mm-long KTA crystal that has been cut for noncritical phase matching along the $\theta = 90^\circ$ and $\phi = 0^\circ$ direction. Type-II polarization geometry was employed to achieve parametric creation [12]. OPO was pumped by a mode-locked Ti:Sapphire laser operating at 780-nm wavelength with 150 femtosecond FWHM pulses at a 76-MHz repetition rate.

Phase matching was achieved yielding a signal at 1133 nm and an idler at around 2500 nm. At the output of the OPO the pump and the signal were filtered out. The idler signal was then focused on the active area of the photodetectors using an iris and infrared lens [13]. These pulses had a 1-ps FWHM.

The temporal response of the photodetectors was measured on a 50-GHz sampling scope and the detectors were biased using a 40-GHz bias tee [14]. Temporal responses of 30- and 60-μm diameter photodetectors were measured as a function

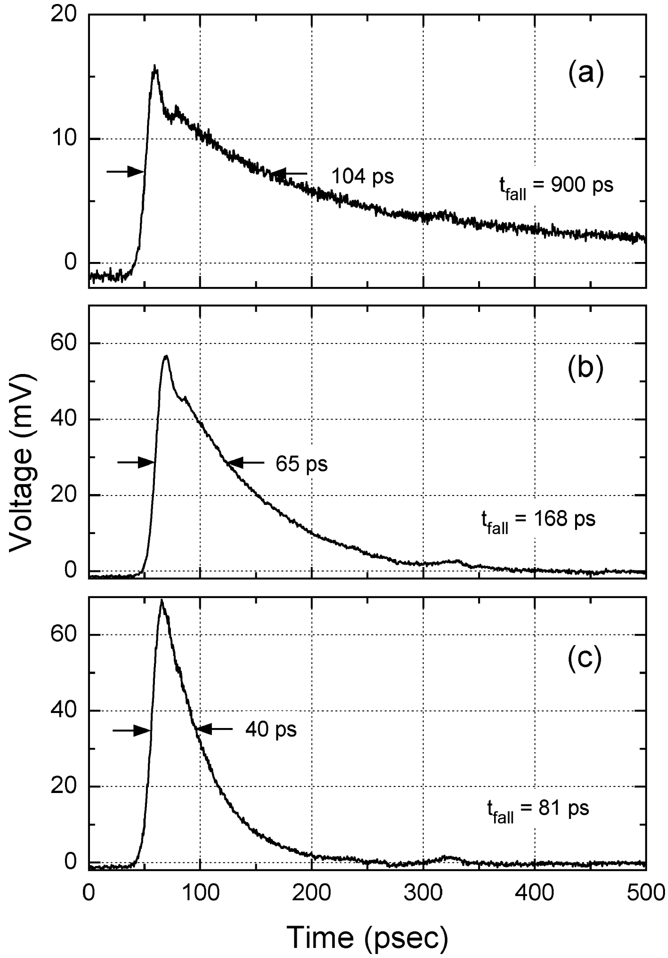

Fig. 8. Temporal response of a 60-μm diameter detector under (a) 0.5-, (b) 1.0-, and (c) 2.5-V bias.

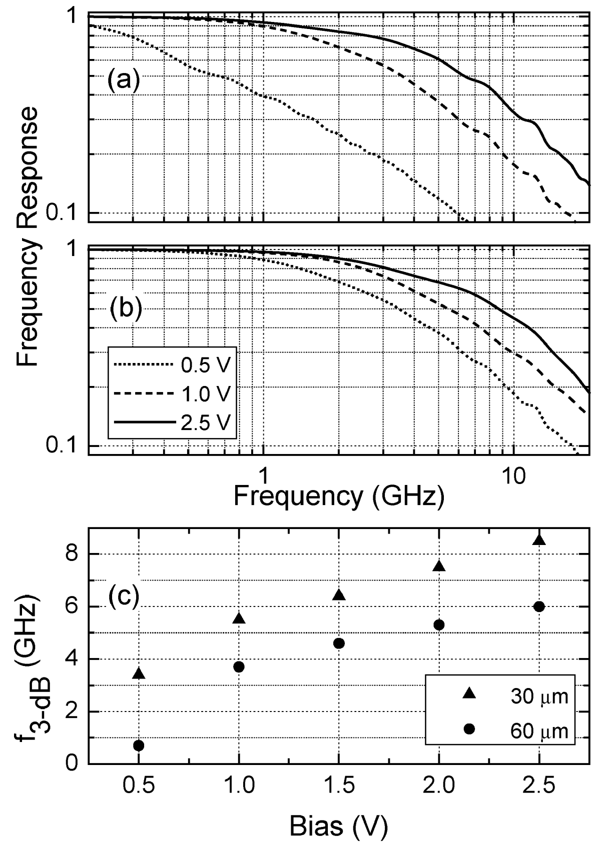

Fig. 9. FFT of the temporal responses of the photodetectors. Results for (a) 60-μm diameter and (b) 30-μm diameter photodetectors as a function of bias are shown. (c) 3-dB bandwidth of the 30- and 60-μm diameter photodetectors as a function of applied bias.

of reverse bias. Without bias, the responses had long tails. This tail was due to the diffusion of carriers in the intrinsic region, which could not be depleted without bias at room temperature. With the application of bias voltage, we observed a reduction of the FWHM of the detector responses. At 0.5 V bias, the FWHM values were measured as 59 and 104 ps for 30- and 60-μm diameter photodetectors, respectively. After 1-V bias, FWHM values decreased linearly with voltage up to 2.5 V. Measured FWHM values for the detectors biased with 1.0 and 2.5 V were 41 and 33 ps for 30-μm and 65 and 40 ps for 60 μm. Figs. 7 and 8 show the temporal response of the 30- and 60-μm diameter photodetectors under 0.5-, 1.0-, and 2.5-V biases. For each detector, both the FWHM and the fall time decreased as we increased the bias voltage. Frequency responses of the detectors were calculated using a fast Fourier transform (FFT). Fig. 9(a) and (b) shows the calculated FFT results of the detectors as a function of bias voltage. Fig. 9(c) shows the 3-dB bandwidth of the detectors as a function of bias. The linear increase in bandwidth with the bias can be seen easily beyond 1.0 V bias. The maximum bandwidth measured for the 30-μm diameter detector was 8.5 GHz. We expect similar or better high-speed responses when the photodetectors are cooled to 77 K. The detector active area should be depleted easier and the diffusion related slow responses can be eliminated. Such high-speed infrared photodetectors can be used for optical heterodyne detection and microwave mixing, infrared laser inspection, and free-space communication [15], [16]. It is known that mid-IR and far-IR wavelength region (3–5 μm, and 8–14 μm) are better than visible or near-infrared regions in terms of transmission and background noise [17].

IV. Conclusion

We have demonstrated the high-speed operation of the InSb-based p-i-n photodetectors in the mid-IR. The detectors showed 33-ps FWHM at 2.5 V bias, corresponding to a 3-dB bandwidth of 8.5 GHz. At low bias voltages, the detectors had 59-ps FWHM, which corresponded to a bandwidth of 3.4 GHz. Responsivity measurements showed that the detectors had high responsivity in the mid-IR where the maximum value was 1.00×10^5 V/W at 4.35 μm for 60-μm diameter detectors.

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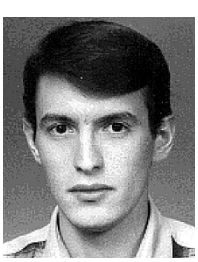

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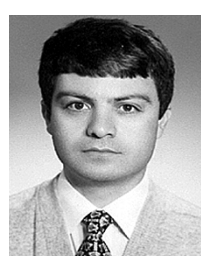

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