Infrared Physics & Technology 70 (2015) 87–92

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

InAs/GaSb superlattice infrared detectors

Robert Rehm *, Florian Lemke, Michael Masur, Johannes Schmitz, Tim Stadelmann, Matthias Wauro, Andreas Wörl, Martin Walther

Fraunhofer-Institut für Angewandte Festkörperphysik (IAF), Tullastr. 72, 79108 Freiburg, Germany

HIGHLIGHTS

- Novel passivation achieves noise reduction in dual-color T2SL-FAPs for the MWIR.
- McIntyre's excess noise model gives better general description of white noise.
- Sidewall contribution must not be ignored for analysis of dark current components.
- Robust Al-free heterojunction T2SL photodiodes demonstrate reduced dark current.

ARTICLE INFO

Article history:
Received 30 July 2014
Available online 7 October 2014

Keywords:
InAs/GaSb superlattice
Infrared focal plane array
Dual-color
Noise
Lifetime
Heterojunction device

ABSTRACT

We report on the development of high-performance InAs/GaSb superlattice (SL) infrared (IR) detectors for the mid-wavelength (MWIR, 3–5 μm) and long-wavelength (LWIR, 8–12 μm) transmission window of the atmosphere. With a refined process technology, we are now able to fabricate dual-color focal plane arrays for the MWIR that excel at a very low number of noisy pixels. In an effort to correlate dark current and noise data of a larger number of devices, we found that for the description of the behavior in the white noise part of the spectrum, both, in InAs/GaSb SL photodiodes for the MWIR and the LWIR McIntyre's well-known model for excess noise of avalanche photodiodes is, in general, much more suited than the commonly used shot noise model. The analysis of dark current contributions is a convenient method to identify limiting mechanisms and extract material parameters such as the minority carrier lifetime. We show that even in large area devices the contribution of the sidewall leakage path should not be ignored for this kind of investigation. Finally, we present our Al-free heterojunction device concept for reduced dark current.

1. Introduction

InAs/GaSb superlattice (SL) infrared (IR) detectors allow realizing high-performance single element and array detectors for the 3–20 μm regime. At Fraunhofer IAF, dedicated materials development for antimonide-based SL detectors began in the 1990s [1,2] and has led to the first high-quality imaging IR focal plane array (FPA) InAs/GaSb SL cameras for the mid-wavelength infrared (MWIR, 3–5 μm) range a decade ago [3]. Subsequently, the technology was advanced to enable simultaneous, co-located bispectral detection at 3–4 μm and 4–5 μm, respectively [4]. After several years of detailed root cause analysis and continuous improvements of various front- and backside processes, Section 2 shows that these dual-color InAs/GaSb SL detectors now achieve an excellent noise equivalent temperature difference (NETD) with a very low number of defective pixels [5]. Their extraordinary noise performance makes these detectors well suited for low false alarm missile approach warning systems, which is more challenging than mere imaging applications.

In an effort to empirically characterize the noise behavior of InAs/GaSb superlattice detectors and its relation to the detector dark current, we have noted excess noise in the white part of the noise spectrum. Section 3 outlines these observations, that we have made both in InAs/GaSb SL photodiodes for the MWIR and the long-wavelength infrared (LWIR, 8–12 μm) regime.

It is generally acknowledged, that InAs/GaSb SL photodiodes suffer from a comparatively low minority carrier lifetime that gives rise to increased dark current. A convenient method to extract lifetime data is the fitting of standard photodiode theory to experimental IV-curves. In Section 4, we apply this method to conventional homojunction InAs/GaSb SL photodiodes for the LWIR range. In addition to the extracted lifetime data, limiting current mechanisms can be identified. We show that the common

* Corresponding author. Tel.: +49 761 5159 353; fax: +49 761 5159 71353.
E-mail address: robert.rehm@iaf.fraunhofer.de (R. Rehm).

http://dx.doi.org/10.1016/j.infrared.2014.09.034
1350-4495/

disregard of sidewall contributions may lead to significant misconceptions in this kind of analysis. Interestingly, the investigated material is limited by diffusion instead of generation-recombination (gr) dark current at low reverse bias around 77 K.

In recent years, several research groups have successfully demonstrated that heterojunction device concepts help to overcome the minority carrier lifetime limitation in InAs/GaSb SL detectors. In Section 5, we present a first proof of principle for our "Al-free" heterojunction device concept, which is expected to lead to a robust process technology for LWIR-FPAs with low total dark current.

2. Dual-color detector arrays for missile approach warning systems

At present, most missile approach warning (MAW) systems rely on photocathodes that are sensitive in the solar blind ultraviolet (UV) regime. Aside from suffering from a low range performance, the threat's UV signature is only existent during the relatively short boost phase. A MWIR detector achieves a longer threat detection range and improved reaction time for countermeasures, due to the prominent carbon dioxide line in the exhaust fumes. However, MAW systems relying on the MWIR have to deal with a large number of potential false alarms due to intense broad-band clutter sources like, e.g., sun-light reflections on vegetation or sea. Separating broad-band clutter from narrow-band carbon dioxide signatures therefore helps to bring the number of false alarms down to a level that is manageable even with moderate processing power.

For MAW applications, we have developed a mature manufacturing process for 384×288 dual-color InAs/GaSb SL detector arrays with a pitch size of 40 μm. With two back-to-back homojunction photodiodes, that are contacted by three electrical contacts, each pixel detects a blue (3–4 μm) and a red (4–5 μm) wavelength band simultaneously. Hence, coping with fast changes of the scenery on the system level is therefore straightforward.

Fig. 1 compares NETD histogram data for the blue and red channel on a logarithmic scale. The NETD was measured for a 300 K background with the FPA operated at half-well filling conditions of the read-out integrated circuit (ROIC). The plots in the upper and lower rows represent the NETD distribution of a typical dual-color FPA before (upper row) and after (lower row) implementation of several process improvements. The major change, that has been implemented, is the usage of a novel method for dielectric surface passivation. While the blue channel histogram data is virtually unaffected by the modified process, the noisy pixels responsible for the tail of the NETD distribution have now disappeared and the pixel operability has been increased to values well over 99%. In particular, the refined technology has dramatically reduced the number of pixels displaying burst or random telegraph noise. Due to their similarity to real threats, this aspect is relevant for achieving a low false alarm rate within an MAW system. Further recent details on our dual color technology can be found in Ref. [5].

3. Empirical studies on white noise

In order to gain a better understanding of the noise behavior of InAs/GaSb SL photodiodes and its relation to the dark current of the devices, we have set up a low noise measurement setup [6] to study larger sets of MWIR [7] and LWIR [8] homojunction photodiode devices at 77 K. For these studies, we have used dielectrically passivated mesa devices with a large size of $400 \times 400\ \mu m^2$. The bulk of both the MWIR and the LWIR material is gr-limited and by analyzing the dependence of the total dark current density on the perimeter-to-area ratio of other devices realized on the same test dies we carefully checked that the total current density in the large diodes was dominated by bulk instead of sidewall currents.

In both sets of large area devices, the distribution of the reverse bias dark current showed a significant spread over orders of magnitude and, in particular for the MWIR set, only few large-sized diodes achieved a dark current close to the dark current level of the bulk as represented by the performance of a typical small sized reference diode from the same wafer. This familiar behavior of the dark current of large sized diodes is attributed to the presence of macroscopic defects with typical distances of a few hundred microns. Actually, both in the MWIR and LWIR sets, the diodes, which deviated from the gr-limited bulk performance, showed a linear, i.e., shunt-like, IV-curve.

We have studied the noise behavior in the white part of the noise spectrum at 1500–1600 Hz under −50 mV reverse bias at 77 K. We carefully checked that no diode displayed 1/f-behavior at said bias and frequency range. Despite that, the commonly used and well-known shot noise expression did not explain experimental data we found on the full set of diodes. In fact, the shot noise model only explained the noise of devices with a dark current close to the gr-limited bulk level and the deviation of the experimentally observed noise from the expected shot noise increased with increasing dark current (compare left graph in Fig. 2), i.e., for diodes with shunt-like IV-behavior. We found, that over a wide range of reverse bias the well-known excess noise model developed by McIntyre for avalanche photodiodes could be adapted to fit general behavior of the entire data set for both sets of devices (see right graph in Fig. 2). We could adapt McIntyre's model for electron injection into the high-field domain, when we used the ratio of the device dark current to the reference bulk dark current for the multiplication factor M in McIntyre's model. Furthermore, for MWIR and LWIR devices a different k-ratio, which relates the hole and electron ionization coefficients, had to be used to fit the data (MWIR: $k = 100$, LWIR: $k = 0$).

Tentatively, the presence of high electric field domains around sites of macroscopic defects gives rise to white excess noise in InAs/GaSb SL photodiodes. Nevertheless, these defect sites go along with a linear, shunt-like dark current behavior of the device. Remarkably, it seems that McIntyre's excess noise model is well suited to translate the dark current distribution of a larger set of devices into noise distributions in the white part of the spectrum.

4. Dark current limitations in LWIR homojunction devices

Dark current analysis helps to understand limiting mechanisms and to quantify fundamental material parameters such as carrier lifetime, trap density and background doping. We have developed an interactive software tool that allows fitting of common theoretical models for the diffusion, gr-, trap-assisted tunneling (TAT), direct tunneling (DT) and ohmic shunt contributions to experimental IV-data. For the diffusion component we employ a model for a short diode, because of the generally long diffusion length of minority electrons in InAs/GaSb SLs. Due to the widening of the space charge region (SCR) and the corresponding reduction of the width of the neutral regions, the diffusion current of minority electrons from the p-side decreases with increasing reverse bias, which leads to a bias-dependent behavior of the diffusion component. For the carrier lifetimes governing the diffusion and gr-contributions, respectively, we generally assume $\tau_n = \tau_p \neq \tau_{gr}$ and thus explicitly allow that τ_n and τ_{gr} take different values. The trap energy level is assumed at half of the bandgap. In particular, this assumption influences the numbers extracted for the trap density N_t and τ_{gr}. Furthermore, we take account of the voltage drop over the series