Reducing the cooling requirements of mid-wave IR detector arrays

Philip Klipstein, Daniel Aronov, Eyal Berkowicz, Rami Fraenkel, Alex Glozman, Steve Grossman, Olga Klin, Inna Lukomska, Itay Shtrichman, Noam Snapi, Michael Yassen, and Eliezer Weiss

A new heterostructure radiation detector has less demanding operating condition requirements and allows reduced size, weight, and cooling power.

The mid-wave IR (MWIR) band in the atmosphere is important for thermal sensing because it spans the optical wavelengths (3–5 μm) at which all room-temperature objects emit significant quantities of electromagnetic radiation. Detectors that operate in this range are useful for security applications such as night vision cameras. High-performance photodiode focal plane array (FPA) MWIR detectors are usually made from the semiconductors mercury cadmium telluride (HgCdTe) or indium antimonide (InSb). However, a common limiting factor of detector performance is dark current, which arises from the thermal excitation of charge carriers across the semiconductor bandgap. Reducing dark current is key to advancing MWIR detector performance.

A detector is described as operating in the diffusion limit if the dark current results from minority carriers—such as holes in an n-type semiconductor—that are excited in the photon-absorbing active layer and diffuse with Brownian-like motion to the collecting contact. A diffusion-limited current can be achieved in the best HgCdTe FPAs, which are typically grown on expensive cadmium zinc telluride substrates. In contrast, even the best InSb FPAs are generation-recombination (G-R) limited. In this limit, Shockley-Read-Hall traps—created by imperfections in the semiconductor crystal lattice—provide energy states that lie in the semiconductor bandgap. That is, they act as 'stepping stones' for thermally excited electrons and holes to pass through. In the depletion region—a thin layer at the diode p-n junction—a built-in electric field exists, which separates the electrons and holes before they can recombine. This provides a powerful driving force for the dark current. The dark current in InSb FPAs is therefore significantly greater than in those composed of HgCdTe.

Both InSb and HgCdTe detectors must be cooled cryogenically, typically with a miniature Joule-Thomson or Stirling cycle refrigerator. The detector and refrigeration units are combined in an integrated detector/cooler assembly (IDCA, see Figure 1). The increased dark current in InSb is usually suppressed by operating the FPA at a temperature some tens of degrees Kelvin cooler than the equivalent diffusion-limited

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Figure 2. A schematic Arrhenius plot of the logarithm of dark current (I) against the reciprocal temperature (T) in a diode (solid line) and bariode (dashed line). Below the crossover temperature ($T_0$) generation-recombination (G-R) limited dark current only exists in the diode and not the bariode (no GR). Above $T_0$, the dark current is diffusion limited (DIFF) in both devices.

HgCdTe device. This apparent disadvantage is offset by the increased uniformity and significantly lower cost per pixel of InSb, making it the current favorite for large-scale arrays. Here, we develop a new patented ‘bariode’ technology for indium arsenide antimonide (InAs$_{1-x}$Sb$_x$) devices. This provides low diffusion-limited dark current, but with many of the advantages of InSb. In particular, it can be scaled to large areas at an affordable cost.

William Henry Eccles coined the term ‘diode’ in 1919 from the Greek roots dia, meaning through, and ode (from ὧδης), meaning path. Bariode is a portmanteau of ‘barrier diode’ that describes a semiconductor photodetector with a clear path through the device for minority carriers from the photon-absorbing layer while the path of its majority carriers is blocked by a barrier. The bariode—or XB$_n^n$ detector—has a cut-off wavelength of ~4.2 μm. It is based on a heterostructure design that can be grown with high quality on commercially available substrates using molecular beam epitaxy. The device contains an n- or p-type contact layer (X) made from InAs$_{1-x}$Sb$_x$ or gallium antimonide (GaSb), a barrier layer (B$_n$) from n-type aluminum antimonide arsenide (AlSb$_{1-y}$As$_y$), and an active layer (n) from n-type InAs$_{1-x}$Sb$_x$.

Figure 3. The schematic conduction and valence band profiles under operating bias for the members of the bariode family. (a) n-type (XB$_n^n$) and (b) p-type (XB$_p^p$) bariodes. In each case the contact layer (X) is on the left, and IR radiation is incident onto the active layer on the right. When X is composed of the same material as the active layer, both layers have the same symbol (denoting the doping type), otherwise it is denoted as C (with the doping type as a subscript). B: Barrier layer. Fermi levels are shown as dashed lines.

In our bariode detector, the bulk G-R current is totally suppressed by excluding the depletion electric field from the narrow-bandgap active layer. In doing so, the operating point

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Figure 4. Image registered with an F/3 aperture at 150K on a 15μm pitch indium arsenide antimonide n-type bariode focal plane array with 640 × 512 pixels. The noise-equivalent temperature difference was 20mK.

is only limited by diffusion, substantially increasing the operating temperature without increasing dark current (see Figure 2). Thus, we have achieved XBn,n detector operation with an F/3 aperture at 160K with background-limited performance (BLIP), doubling the traditional InSb operating temperature. The small aperture is useful because it has a high level of magnification. Additionally, this high-temperature operation requires less than 50% of the cooling power, so a much smaller cooling unit is needed. Altogether, the bariode enables substantial reductions in the required cooling power, size, and weight of the complete IDCA.

We developed four types of XBn,n n-type bariode devices (see Figure 3). While all have the same n-type Bn,n structural unit, we used different contact layers (X), where either the doping, material, or both are varied. All should perform identically, which we showed for CnBn,n and nBn,n devices, where the contact layer is Cn or n, respectively. Specifically, Cn is a p-type contact made from a different material to the active layer, whereas n is an n-type contact made from the same material. The same doping type in the barrier and active layers is key to maintaining low, diffusion-limited dark current. This creates the interesting situation of a completely unipolar nBn,n device that behaves in many ways like a photovoltaic detector, even though it does not contain a p-n junction. Our bariode family also has p-type members, designated XBp,p bariodes: see Figure 3(b). The XBp,p bariodes are polarity-reversed versions of the n-type bariodes.

Such structures can be realized using a p-type InAs/GaSb type II superlattice as the photon absorbing layer. We used an InAs1−xSbx 15μm pitch n-type bariode FPA, operating under BLIP conditions to register an image at 150K with an F/3 aperture (see Figure 4). It was flip-chip bonded to a 640 × 512 pixel silicon CMOS read-out integrated circuit. The small black features in the image are cows ~1–2km away. The measured noise-equivalent temperature difference (NETD) was 20mK at 22ms integration time, and the operability of non-defective pixels was greater than 99.5%. We have also operated a 320 × 256 pixel, 30μm pitch FPA at 180K and F/3. Although not BLIP, we obtained a reasonable NETD of 43mK and registered a clear image. We expect to reduce the integration time substantially in future generation devices.

In summary, our bariodes are new III-V semiconductor heterostructure devices with a suppressed G-R dark current that operate at higher temperatures compared to standard InSb FPAs. These are expected to provide enhanced solutions for applications where reduced size, weight, and required cooling power are critical. They should also be useful in low incident flux applications where very low dark current is needed. We have fabricated a number of high-performance n-type bariode demonstration FPAs with pitches of 15-30μm, operating at 150–180K. Our future research plans include varying the detector cut-off wavelength, increasing the FPA sensitivity, and reducing its pitch.

Author Information

Philip Klipstein, Daniel Aronov, Eyal Berkowicz, Rami Fraenkel, Alex Glozman, Steve Grossman, Olga Klin, Inna Lukomsky, Itay Shtrichman, Noam Snapi, Michael Yassen, and Eliezer Weiss

SemiConductor Devices
Haifa, Israel

Philip Klipstein received his BA and PhD degrees from the Universities of Oxford and Cambridge, respectively. After spending 15 years in tenured academic posts at Imperial College London and Oxford University he joined SemiConductor Devices in 2000.

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