Single-Photon-Sensitive HgCdTe Avalanche Photodiode Detector

Detector provides extra dimension to lidar scene data for multi-photon returns.

Goddard Space Flight Center, Greenbelt, Maryland

The purpose of this program was to develop single-photon-sensitive short-wavelength infrared (SWIR) and mid-wavelength infrared (MWIR) avalanche photodiode (APD) receivers based on linear-mode HgCdTe APDs, for application by NASA in light detection and ranging (lidar) sensors. Linear-mode photon-counting APDs are desired for lidar because they have a shorter pixel dead time than Geiger APDs, and can detect sequential pulse returns from multiple objects that are closely spaced in range. Linear-mode APDs can also measure photon number, which Geiger APDs cannot, adding an extra dimension to lidar scene data for multi-photon returns. High-gain APDs with low multiplication noise are required for efficient linear-mode detection of single photons because of APD gain statistics — a low-excess-noise APD will generate detectible current pulses from single photon input at a much higher rate of occurrence than will a noisy APD operated at the same average gain. MWIR and LWIR electron-avalanche HgCdTe APDs have been shown to operate in linear mode at high average

avalanche gain (M > 1000) without excess multiplication noise (F = 1), and are therefore very good candidates for linear-mode photon counting. However, detectors fashioned from these narrow-bandgap alloys require aggressive cooling to control thermal dark current. Wider-bandgap SWIR HgCdTe APDs were investigated in this program as a strategy to reduce detector cooling requirements.

The first objective was to build SWIR HgCdTe APDs, and to assess their suitability for photon counting in linear mode. The second objective was to implement manufacturing improvements to mitigate surface dark current, improve reliability, and eliminate peaking in the spectral response.

Voxtel manufactured and characterized 2.7-µm-cutoff HgCdTe APDs, publishing excess noise data taken at the highest avalanche gain levels yet demonstrated for SWIR HgCdTe APDs (M = 80). Quantum efficiency was limited to approximately 73% at 1,550 nm by partial reflection from the non-coated optical entrance surface; quantum efficiency near 94% is expected for these devices if

an anti-reflection coating is used. Excellent yield of operable APD pixels and uniformity of APD response were both obtained, but the maximum avalanche gain that could be achieved with SWIR-cutoff material was deemed too low to enable single-photon detection. Comparison of Voxtel's maximum gain measurements suggests that this is an inherent material limitation of the SWIR alloy. Room-temperature responsivity of about 5 kV/W and noise-equivalent power (NEP) of 33.3 nW were measured at 1550 nm when the APD operated at a gain of M=6.6.

Completion of development of CdTe surface passivation for MWIR HgCdTe APDs presents the best opportunity to further improve receiver sensitivity, as it will enable operation at much higher avalanche gain with reduced dark current. This innovation can find use with quantum information (encryption and basic science), semiconductor inspection, and molecular spectroscopy.

This work was done by Andrew Huntington of Voxtel, Inc. for Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-16140-1

Surface-Enhanced Raman Scattering Using Silica Whispering-Gallery Mode Resonators

Silica sphere optical resonators are used to provide surface-enhanced spectroscopic signal.

NASA's Jet Propulsion Laboratory, Pasadena, California

The motivation of this work was to have robust spectroscopic sensors for sensitive detection and chemical analysis of organic and molecular compounds. The solution is to use silica sphere optical resonators to provide surface-enhanced spectroscopic signal.

Whispering-gallery mode (WGM) resonators made from silica microspheres were used for surface-enhanced Raman scattering (SERS) without coupling to a plasmonic mechanism. Large Raman signal enhancement is observed by exclusively using 5.08-micron silica spheres with

785-nm laser excitation. The advantage of this non-plasmonic approach is that the active substrate is chemically inert silica, thermally stable, and relatively simple to fabricate. The Raman signal enhancement is broadly applicable to a wide range of molecular functional groups including aliphatic hydrocarbons, siloxanes, and esters. Applications include trace organic analysis, particularly for in situ planetary instruments that require robust sensors with consistent response.

WGM SERS using microspheres or quartz surface structures provide a chem-

ically robust surface for sensor applications that could be cleaned by resistively heating the sensor element. This is particularly useful for spacecraft instruments used for the detection of organics in planetary soils. The conventional silver-based SERS substrates are limited by reactivity of silver. In the case of gold SERS substrates, high temperatures (<200 °C) will cause diffusion in the gold that degrades the nanostructure. The use of WGM SERS may also be used for surface analysis in a manner similar to attenuated total reflectance used in infrared spec-

troscopy. The surface localized field enhancement could be used to probe the upper layers of a sample surface.

WGM resonances (1, 2, X =also termed morphology-dependent resonances) take place when an incident light becomes trapped near the inner surface of a particle resulting from total internal reflection. This results in enhancement of the evanescent electromagnetic field at certain nodes near the surface of the particle. WGM resonance structures have been proposed as chemical sensors and when coupled with conventional Plasmon-based SERS, for single-molecule spectroscopy.

Very large enhancements are feasible by using 5-micron silica microspheres. Enhancement factors comparable to those seen from noble metal spheroids are possible enhancements when the Raman-scattered radiation also overlaps with a WGM resonance. For microspheres with radius of 5 microns, the enhancement factor can exceed an order of magnitude. This is a significant result that indicates that it would be possible to observe SERS with non-resonant scatterers.

This work was done by Mark S. Anderson of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov.

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, NASA Management Office–JPL. Refer to NPO-47604.t

3D Hail Size Distribution Interpolation/Extrapolation Algorithm
Multiple sensors are not required.

John F. Kennedy Space Center, Florida

Radar data can usually detect hail; however, it is difficult for present day radar to accurately discriminate between hail and rain. Local ground-based hail sensors are much better at detecting hail against a rain background, and when incorporated with radar data, provide a much better local picture of a severe rain or hail event.

The previous disdrometer interpolation/extrapolation algorithm described a method to interpolate horizontally between multiple ground sensors (a minimum of three) and extrapolate vertically. This work is a modification to that approach that generates a purely extrapolated 3D spatial distribution when using a single sensor.

A 3D high-resolution mapping of hail, as well as rain, is desirable in many instances. For example, hail mapping in the vicinity of a launch vehicle on the launch pad would help determine whether or not damage has occurred following a hail event. In addition to quantifying the size and quantity of hail, it is desirable to know where on the vehicle hail impacts may have occurred. A method that was previously developed, and that required multiple ground sensors, has been modified to accommodate a single sensor. The 3D extrapolation from a single (or multiple) ground sensor can then be compared to the 3D radar-generated spatial map.

The 3D hydrometeor size interpolation scheme described in previous work assumes that a minimum of three hydrometeor disdrometers (rain or hail) are required for successful interpolation/extrapolation of the hydrometeor distribution in time and space. By simply bypassing the "gravity interpolation algorithm" for multiple sensors, it is shown that good agreement between single sites vs. multiple sites vs. radar is obtained.

The software modification allows any number of sensors, from 1 to *N*, to be used in the 3D-DSD algorithm. As would be expected, the more sensors that are available, the better, but the requirement for a minimum of three sensors has now been eliminated. This disclosure demonstrates that multiple sensors are not required for successful implementation of the 3D interpolation/extrapolation algorithm. This is a great benefit, since it is seldom that multiple sensors in the required spatial arrangement are available for this type of analysis. This can be used in conjunction with a single sensor or an array of hail monitors, or single or multiple rainfall disdrometers.

This work was done by John Lane of ASRC Aerospace Corporation for Kennedy Space Center. Further information is contained in a TSP (see page 1). KSC-13244

Color-Changing Sensors for Detecting the Presence of Hypergolic Fuels
Chemochromic pigment indicates the presence of hypergols, improving workers' safety.

John F. Kennedy Space Center, Florida

Hypergolic fuel sensors were designed to incorporate novel chemochromic pigments into substrates for use in various methods of leak detection. There are several embodiments to this invention that would provide specific visual indication of hypergols used during and after transfer. The ability to incorporate these pigments into various polymer matrices provides a unique opportunity to manufacture nearly any type of sensor shape that is required. The vibrant color change from yellow to black instantaneously shows the worker the presence of hypergols in the area, providing the worker the ability to immediately evacuate the area.

The chemochromic pigments are prepared in powder or liquid form for addition into many different materials in different articles. With the ability to incorporate the pigment into a wide range of materials, the sensor can take any embodiment allowed by various manufacturing methods. For example,