Title
1/f noise in all-epitaxial metal-semiconductor diodes

Journal
Applied Physics Letters, 88(7)

ISSN
0003-6951

Authors
Young, Adam C
Zimmerman, J D
Brown, E R
et al.

Publication Date
2006-02-01

DOI
10.1063/1.2174837

Peer reviewed

1/*f* noise in all-epitaxial metal-semiconductor diodes

A. C. Young,[a] J. D. Zimmerman, E. R. Brown, and A. C. Gossard
University of California Santa Barbara, Santa Barbara, California 93106

(Received 25 October 2005; accepted 23 January 2006; published online 17 February 2006)

In contrast to traditional metal-semiconductor (i.e., Schottky) junctions, molecular beam epitaxy (MBE)-grown ErAs:InAlGaAs heterojunctions have recently been shown to provide highly "engineerable" electrical rectification characteristics through the tuning of the Schottky barrier height, while maintaining the very low specific capacitance. This letter reports an approximate 10× improvement in the low-frequency noise performance by using MBE-grown ErAs as the Schottky contact instead of evaporated aluminum. The low-frequency noise power spectrum of ErAs devices has been observed to have a $1/f^{1.0}$ frequency dependence. Constant-current bias-dependent measurements have shown a 1.8 power law dependence of the noise spectral density on dc current. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2174837]

Focal plane arrays for millimeter and submillimeter imaging have recently been generating much interest for possible use in concealed weapons detection, product inspection, and medical imaging applications. To make large-scale focal plane arrays, an easily scalable sensitive detector is needed. A passive detector (i.e., a detector which does not require a source) is also advantageous due to the limited number of sources in this region and their relatively low power levels, making a heterodyne system difficult even before scaling to an array is introduced. The Schottky diode has had widespread success in the microwave- and millimeter-wave regimes, but typical Schottky diodes are not well suited for imaging applications due to their high-noise levels. These high-noise levels are a consequence of the introduction of oxides, contaminants, and damage to the junction in the fabrication process. This letter examines an alternative method to form Schottky diodes, namely an *in situ*, epitaxially grown semimetal-semiconductor junction. While an epitaxially grown Schottky diode has been done before with aluminum, this work uses single-crystal ErAs to prevent interdiffusion and the formation of third phases at the interface.[1]

ErAs is a semimetal with the rocksalt (i.e., NaCl) crystal structure and, most importantly, a lattice constant of 5.74 Å. This is close enough to both GaAs (5.65 Å) and InP (5.87 Å) that high-quality epitaxial films (up to ~75 Å) of ErAs can be grown by molecular beam epitaxy (MBE) on either of these two popular substrates, or on $In_xAl_{1-x-y}Gy_yAs$ lattice matched to InP.[2] An epitaxial single-crystal, nearly lattice-matched semimetal-semiconductor system, such as ErAs:InAlGaAs, should result in lower interface defect densities, a major source of low-frequency noise.[3]

The use of a zero-bias Schottky rectifier simplifies detector design, eliminates biasing circuitry and related noise, and reduces current-induced modulation (flicker and burst) noise, resulting in a room-temperature square-law detector with a noise floor potentially less than 10^{-12} W/Hz$^{1/2}$. To design an efficient detector, we need to maximize responsivity, minimize noise, impedance match the source and the detector diode, and control the capacitance of the device. This letter examines the behavior of ErAs:InAlGaAs through the use of low-frequency noise measurements. Low-frequency noise is of paramount importance in an imaging system where video frame rates of 30 Hz are typical.

Our zero-biased rectifier consists of an ErAs contact layer on $(In_{0.52}Al_{0.48}As)_X(In_{0.53}Ga_{0.47}As)_{1-X}$ (i.e., InAlGaAs) lattice matched to InP. The ErAs and InAlGaAs were grown by MBE at $T_{sub}=490\ °C$, followed by a 750 Å Al capping layer grown in the MBE chamber after cooling to $T_{sub} \leq 50\ °C$.[2] We use an InAlAs:InGaAs digital alloy to allow for tuning of the InAlGaAs composition for a specific application. The contact is thermodynamically stable, robust, and eliminates the possibility of oxide formation at the interface.[4] By varying the composition of the InAlGaAs, the Schottky barrier height and thus the rectifying behavior of the diode, can be changed drastically.[2]

Low-frequency noise spectra were measured using a custom two-stage low-noise amplifier based on the Analog Devices 797 operational amplifier. The amplified output was low-pass filtered at 5 kHz by a Krohn-Hite 3202 filter to prevent aliasing and then sampled by a Measurement Computing PMD 1608-FS running at 16384 samples/s for 10 or 16 s. MATLAB was used to control the PMD 1608-FS as well as to perform data analysis, which included a total-input fast Fourier transform.

The samples were probed using 100 μm pitch ground-signal-ground probes on a Suss probe station placed on a sheet of mu-metal to reduce electromagnetic interference. Evident from the spectra, some 60 Hz (and harmonics) interference still existed and the PMD 1608-FS USB communications added coherent noise to the spectra in the 500 Hz and above range.

To minimize the effects of the amplifier leakage current, the system was ac coupled at approximately 0.5 Hz prior to the first amplifier stage. Biasing was done using 12 V lead-acid batteries (which also powered the amplifiers) and a large metal-film resistor in series with the diode to act as a quasi-constant current source.

In keeping with previously reported work, we have investigated the low-frequency noise of samples having a 20% $In_{0.52}Al_{0.48}As$ composition fraction.[5] That work investigated the radio-frequency (rf) noise performance by measuring the specific noise equivalent power which is a combination of noise, responsivity, and matching efficiency. This work examines the noise directly. The 20% $In_{0.52}Al_{0.48}As$ composi-

[a]Electronic mail: younga01@ece.ucsb.edu

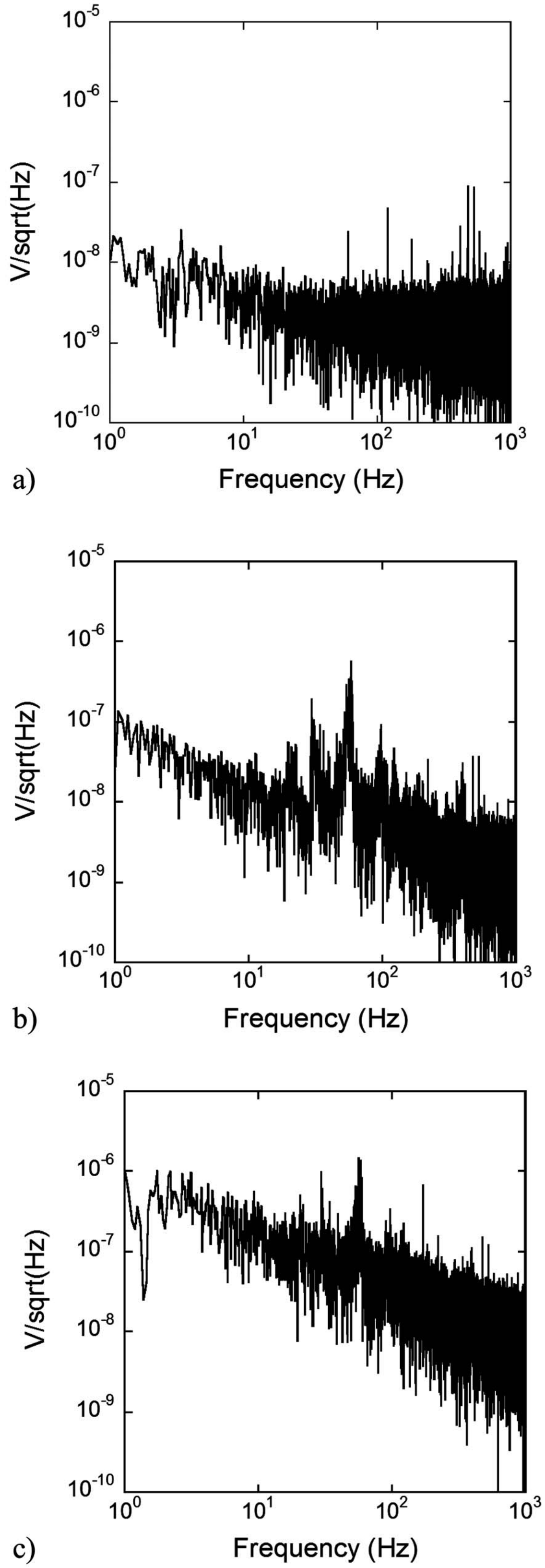

FIG. 1. Noise spectrum of ErAs:InAlGaAs 100 μm diameter mesa diode with (a) 0 μA and (b) 10 μA. (c) Noise spectrum of an Al:InAlGaAs 100 μm diameter mesa diode with 10 μA.

tion was shown to offer the best impedance/short-circuit responsivity trade-off at frequencies between 3 and 8 GHz. Typically, in low-frequency noise measurements, the device is examined under its biasing conditions, however for a zero-bias device, this is of little interest since the excess noise sources generate noise only when there is a net current flow. In this work, the diodes were biased much higher than normal operating conditions to ease the noise demands on the measuring system. To accurately measure these devices under normal operating conditions, the measuring system would need a noise level of less than 1 nV/$\sqrt{}$Hz at 1 Hz, a very difficult task with today's technology. A 100 μm ErAs:InAlGaAs mesa diode with a 20% $In_{0.52}Al_{0.48}As$ composition fraction and an Al:InAlGaAs control sample were measured at 0, 10, 24, 1250, and 40,000 μA.

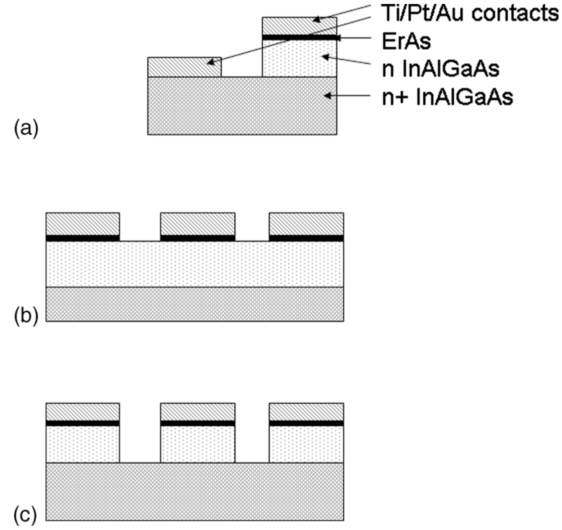

FIG. 2. Diode geometry for (a) a single diode, and back-to-back ErAs contacted diodes (b) without sidewalls and (c) with sidewalls.

The 0 μA data shown in Fig. 1(a), represents the thermal noise of the diode plus the system noise. The most dominant features in the biased power spectrum of Fig. 1(b), are the low-frequency peaks, the largest being at 20, 30, 40, 57, and 100 Hz. These are believed to be low-frequency oscillations similar to those observed in low-temperature GaAs which have been used most recently to investigate routes to chaotic behavior by the nonlinear systems community.[6] A number of theories have been developed to explain this phenomenon, most notably field-enhanced trapping such as that of the EL2 defect.[7,8]

By using a short circuit in place of the diode, the slope of the noise voltage spectrum for the system was measured to be −0.94, giving a $1/f^2$ type of noise power spectrum; the value at 1 Hz is 9×10^{-9} V/$\sqrt{}$Hz. As the bias current is increased, the $1/f^2$ behavior is replaced by a $1/f$ behavior. This occurs not because the amplifier noise is changing character, but because the noise of the diode begins to dominate that of the system. By 1250 μA, the diode noise dominates that of the system. The $1/f$ noise power was found to follow a 1.8 power-law dependence on bias current up to 40 mA, which is approaching the linear region of the current-voltage curve for this particular diode.

Bias dependent studies were also used to investigate the low-frequency oscillations near 30 Hz and 50 Hz. We find that at low current levels, 1250 μA and below, the 30 Hz peak follows a 1.9 power law and the 50 Hz peak a 1.8 power-law dependence. It is unknown why the peaks deviate from this dependence as the bias is further increased and only a small increase in amplitude is seen after increasing the current beyond 1250 μA.

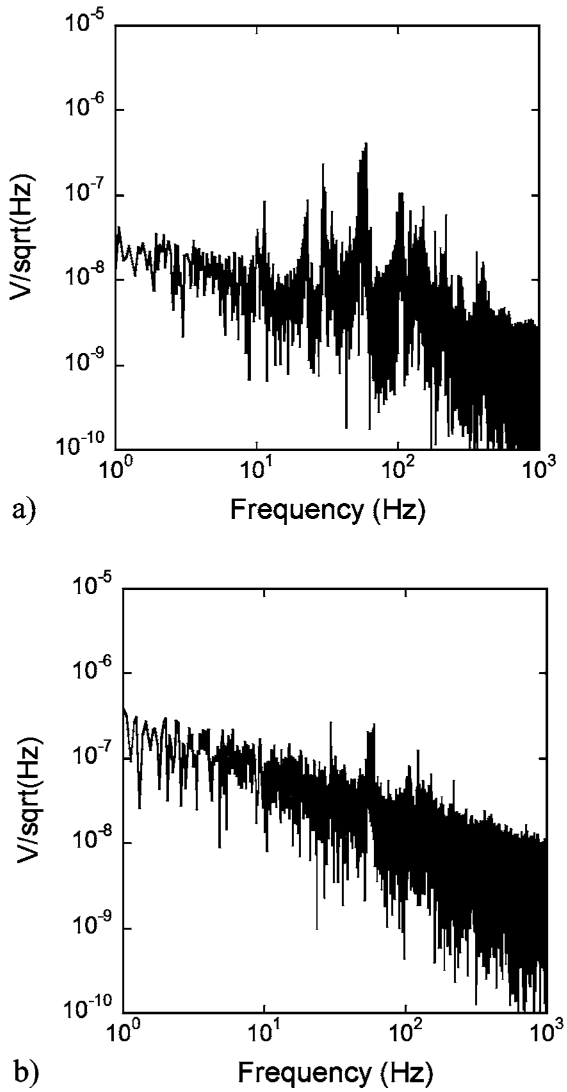

FIG. 3. Noise spectrum of back-to-back ErAs contacted diodes under 1.3 mA bias (a) without sidewalls and (b) with sidewalls.

In addition to the bias dependent studies, a comparison was done between the ErAs:InAlGaAs diode and an Al:InAlGaAs diode, both from the same wafer. The aluminum contact sample was made by removing the ErAs layer in hydrochloric acid and then depositing Al in an electron-beam evaporator. The aluminum Schottky is seen to have approximately 10× higher $1/f$ noise than the ErAs diode for comparable current densities, but still average for an aluminum Schottky diode [Fig. 1(c)]. An important observation is that the low-frequency oscillations are also present in the aluminum Schottky sample with similar amplitudes, supporting the theory that they are due to a trapping process in the bulk.

To further investigate the source of noise in the ErAs:InAlGaAs Schottky diode, special samples were fabricated to identify the regions of the device responsible for the $1/f$ noise. To investigate the cathode contacts, Ti/Pt/Au contacts were placed only on the $n+In_{0.53}Ga_{0.47}As$ bottom contact, and the noise was measured. The noise was dominated by the measurement system, indicating this region is not a significant contributor. The same was true when contacts were made to a continuous Al/ErAs layer. To investigate sidewall noise, back to back (cathode-to-cathode) Schottky diodes were fabricated with and without sidewalls (Fig. 2). The sample without sidewalls still had the top InAlGaAs layer exposed, so some $1/f$ noise due to oxidation was expected. By comparing the samples with and without sidewalls (Fig. 3), it is readily apparent that the sidewalls contribute a significant amount of $1/f$ noise. Comparing Figs. 1(b) and 3, and adjusting for sidewall area and current density, we find that the $1/f$ noise in the ErAs:InAlGaAs diodes can largely be attributed to the sidewalls.

These noise findings support our earlier work on the NEP of ErAs:InAlGaAs diodes, which was 8.9×10^{-13} W/$\sqrt{\text{Hz}}$ at 3.1 GHz for a 20 μm diameter diode.[5] We attribute this to the "cleaner" and lower noise contact that ErAs provides compared to the traditional evaporated Al contact with the added benefit of increased uniformity across the wafer.[2] The ErAs:InAlGaAs also enables the fabrication of low-barrier and low-capacitance devices, making possible zero-bias detectors with very high cut-off frequencies. The ErAs:InAlGaAs materials system has great promise for sensitive room-temperature square-law detectors, envelope detectors, and mixers.

[1]A. Y. Cho and P. D. Dernier, J. Appl. Phys. **49**, 3328 (1978).
[2]J. D. Zimmerman, A. C. Gossard, and E. R. Brown, J. Vac. Sci. Technol. B **23**, 1929 (2005).
[3]S. Kogan, *Electronic Noise and Fluctuations in Solids* (Cambridge University Press, Cambridge, UK, 1996).
[4]C. J. Palmstrøm, *Contacts to Semiconductors: Fundamentals and Technology* (Noyes, New Jersey, 1993).
[5]A. C. Young, J. D. Zimmerman, E. R. Brown, and A. C. Gossard, Appl. Phys. Lett. (to be published).
[6]R. L. da Silva, H. A. Albuquerque, R. M. Rubinger, A. G. de Oliveira, G. M. Ribeiro, and W. N. Rodrigues, Physica D **194**, 166 (2004).
[7]B. K. Ridley and P. H. Wisbey, Br., Br. J. Appl. Phys. **18**, 761 (1967).
[8]M. Kaminska, J. M. Parsey, J. Lagowski, and H. C. Gatos, Appl. Phys. Lett. **41**, 989 (1982).