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

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Low-frequency noise in epitaxially grown Schottky junctions

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

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The low-frequency power spectrum has been measured for ErAs:InAlGaAs diodes and shows at least a ten-times reduction of $1/f$ noise compared to traditional Al Schottky diodes on the same semiconductor material. These junctions are grown by molecular beam epitaxy, preventing oxidation and other contamination at the junction. The major noise source for these devices is attributed to the sidewalls and not the junction itself. Low-frequency oscillations have also been observed and associated with a deep trap level estimated to be ~200 meV below the conduction band edge by the comparison of diodes with different InAlGaAs compositions and confirmed by deep level transient spectroscopy. This deep level could be associated to erbium incorporation in the depletion region. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2721774]

I. INTRODUCTION

Focal plane arrays for millimeter and submillimeter imaging have been generating much interest recently for their possible use in concealed weapons detection, product inspection, and medical imaging applications. While detection of concealed objects can be done with x-ray or infrared technologies, imaging with millimeter and submillimeter wave radiation has two distinct advantages: it is nonionizing and the attenuation through clothing is much reduced.[1] For real-time video imaging, scanning techniques are cumbersome and require very sensitive detectors because of the limited time on target of the detector, leading to the desire for large scale focal plane arrays. The challenge of a focal plane array is to find a sensitive and easily scalable technology. Coherent detectors, such as mixers in a heterodyne system, are difficult to implement due to the relatively low power levels and poor efficiency of compact coherent terahertz (THz) sources. This lack of appropriate sources, coupled with the desire to create large arrays, favors a "direct"-detection approach using an easily fabricated detector such as the Schottky diode.

The Schottky diode has had widespread success in the millimeter-wave and THz regions; however, the typical Schottky diode is not ideal for imaging applications. Their high low-frequency noise levels under bias (from the introduction of oxides, contaminants, and damage to the junction in the fabrication process) require more complicated system architectures which can become burdensome in a large array. This article utilizes an alternative method to Schottky formation, an *in situ*, molecular beam epitaxy (MBE) grown, epitaxial single-crystal metal layer to reduce the imperfections that give rise to excess low-frequency noise, particularly $1/f$ noise. While MBE grown Schottky diodes have been made before with aluminum,[2] the present work uses single-crystal ErAs to maintain crystallinity across the junction, prevent interdiffusion, and inhibit the formation of third phases at the interface.

In traditional Schottky diodes, the metal-semiconductor interface marks the termination of the single-crystal semiconductor and the beginning of a polycrystalline metal. The difference in crystal structure and lattice constant between the two leads to a reconstruction at the interface. This reconstruction is imperfect, however, leaving dangling bonds and their associated trap levels. Unfortunately, this means that even if all surface oxides and contaminants can be avoided, deep traps can still exist at the interface. To reduce the number of dangling bonds at the interface, one should choose a "metal" which has a similar crystal structure and lattice constant in an attempt to reduce the number of broken bonds at the interface. The ErAs:GaAs and ErAs:InAlGaAs systems are well-suited for this purpose. ErAs is a semimetal with the rocksalt (i.e., NaCl) crystal structure and 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 MBE on either substrate, or on $In_xAl_{1-x-y}Ga_yAs$ films lattice-matched to InP as done here.[3] When grown by MBE, interface contamination and oxide formation should be minimized. The concentration of broken bonds at the rocksalt:zinc blende interface should be greatly reduced with respect to an oxide and contaminant free polycrystalline-metal:semiconductor interface, such as Pt:InGaAs.

The rectifying behavior of the diode can be precisely controlled through changing the Schottky barrier height, by varying the composition of the InAlGaAs, and altering the doping concentration in the depletion region.[3,4] These changes have profound affects on the differential resistance, responsivity, and capacitance of the diode, which provides design flexibility. This article examines how the design of the diode affects the low-frequency noise performance, which is of paramount importance for an imaging system using typical video frame rates of 30 Hz.

II. NOISE THEORY

A. $1/f$ noise

Three major types of noise exist in semiconductor devices: thermal, shot, and modulation. While thermal and shot noise are frequency independent and are typically simple functions of the device resistance and current, modulation

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

noise is often characterized by having a $1/f$ type noise power spectral density and proportional to some power of the average current.[5] In traditional Schottky diodes under significant bias, this modulation noise dominates the low-frequency end of the noise spectrum.

Modulation noise can be explained by fluctuations in either the mobility or the number of charged carriers producing a change in the resistance, and consequently of the current and/or voltage measured.[5] Modulation noise is not a current or voltage fluctuation per se, but rather affects any current or voltage through or across the device. Burst, generation-recombination, popcorn and $1/f$ noise are all examples of modulation noise. For a discussion of modulation noise see Ref. 5.

B. Low-frequency oscillations

Low-frequency oscillations in some GaAs devices have been observed and studied for over 40 years. A number of theories have been developed to explain these oscillations, most notably theories based on field-enhanced trapping and charge depletion regions at the electrodes that are larger than the carrier diffusion lengths.[6–8] In the case of the Schottky diodes tested in this article, field-enhanced trapping seems to be the appropriate explanation. In field-enhanced recombination, the trapping process is more efficient for hot carriers than those at thermal equilibrium. This energy selectivity can be explained by a trap surrounded by a repulsive potential barrier where the hot carrier has an increased probability to either tunnel through or surmount the barrier.[6] Additional possibilities include configurational barriers and efficient trapping from subsidiary band minima (i.e., the X or L valleys).[6]

In an attempt to explain low-frequency oscillations in germanium, Ridley and Wisbey have shown through a series of models that field-enhanced trapping can create propagating charge density domains.[7] While Ridley and Wisbey[10] were concerned with describing the macroscopic behavior of low-frequency oscillations, Kaminska *et al.*[6] investigated the microscopic behavior of a certain class of traps which could have field-dependent trapping characteristics. Kaminska *et al.* suggested a configurational model to explain field-enhanced trapping of the $EL2$ defect in GaAs. Their argument is based on a more efficient multiphonon emission process in the $EL2$ defect for hot electrons than for thermalized electrons.[6] A simpler model would be a defect with a repulsive barrier; however this model is not acceptable for a donor-like defect such as the $EL2$ defect, but may in fact be appropriate here.

III. SAMPLES AND FABRICATION

The material used here was grown using a Varian Gen II MBE system equipped with an erbium effusion cell. All samples were grown on InP substrates with a 7000 Å n^+ $In_{0.53}Ga_{0.47}As$ bottom contact layer, a 1000–2000 Å thick layer, linearly graded from $In_{0.53}Ga_{0.47}As$ to the desired InAlGaAs composition, and doped with 5×10^{18} cm^{-3} of Si, a 1000 Å InAlGaAs depletion region doped with 1×10^{17} cm^{-3} of Si, and a 75 Å layer of ErAs capped with 750 Å of Al to prevent oxidation of the ErAs. The semiconductor layers and ErAs were grown at 490 °C (pyrometer) and the Al capping layer was grown at <50 °C (thermocouple). Further details of the growth can be found in Ref. 3.

TABLE I. Sample list detailing the InAlGaAs composition, Schottky contact material, and presence of sidewalls.

Composition (%)	Contact	Sidewalls
0	ErAs	Yes
10	ErAs	Yes
20	ErAs	Yes
30	ErAs	Yes
80	ErAs	Yes
100	ErAs	Yes
20	ErAs	No
20	Al	Yes

The digital alloy is grown by using a short-period (10 Å) superlattice shuttering sequence that alternately deposits thin layers of $In_{0.53}Ga_{0.47}As$ and $In_{0.48}Al_{0.52}As$. The 10 Å period is sufficiently thin that the superlattice approximates a traditional quaternary alloy's electrical properties. Digital alloying also makes grading the composition easier.

The samples tested here are 100 μm diameter mesa diodes fabricated using standard photoresist, contact lithography, and lift-off techniques. After patterning the top contact circle in photoresist, Ti (100 Å)/Pt (200 Å)/Au (3000 Å) films were deposited in an electron-beam evaporator in a single pump down process followed by a metallization lift-off. The exposed Al was removed by etching for approximately 2 min with de-ionized water:AZ400K, mixed 4:1. To remove the now exposed ErAs and etch to the n^+ InGaAs layer, a wet etch of citric acid (1 M):H_2O_2 (30%), mixed 50:1 was used. The bottom Ohmic contacts were defined and Ti (100 Å)/Pt (200 Å)/Au (3000 Å) layers were deposited, followed by a lift-off. Several variations of this technique were used to change the relative location of the sidewalls and to test the Ohmic contacts and the Al/ErAs top layer (see Sec. IV D). Table I lists the different samples fabricated for this work.

IV. RESULTS

A. Experimental setup

The low-frequency noise spectrum of various samples was measured using a custom battery powered two-stage low noise amplifier (LNA) based on a Linear Technologies 1028 (first stage) and an Analog Devices 624 instrumentation amplifier. The amplified output was low-pass filtered at 5 kHz with a Krohn-Hite 3202 filter to prevent aliasing and then sampled by a Measurement Computing PMD 1608-FS data acquisition unit running at 16 384 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 fast Fourier transform.

The samples were contacted using 100 μm pitch ground-signal-ground probes on a Suss PM-5 probe station placed on a sheet of mumetal to reduce 60 Hz interference. Some 60

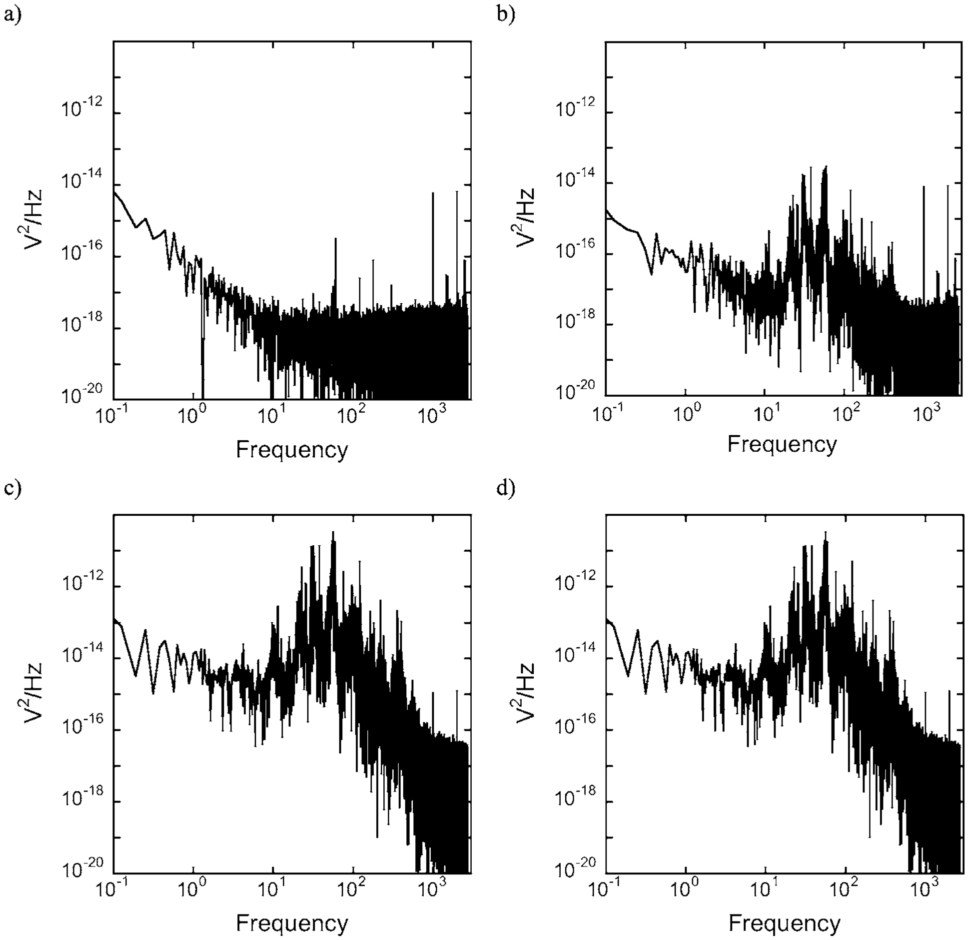

FIG. 1. Low-frequency noise spectrum for a 20% InAlAs composition ErAs contacted diode with (a) 0, (b) 24, (c) 1250 and (d) 40 000 μA.

Hz (and harmonics) interference still existed and the PMD 1608-FS USB communications also added coherent noise in the 500 Hz and above range.

To minimize the effects of the amplifier leakage current, the system was alternating current-coupled at ~0.5 Hz prior to the first amplifier stage using polyester capacitors. Biasing was done using 12 V lead-acid batteries (which also powered the amplifiers) and various large metal-film resistors in series with the diodes to act as a quasiconstant current source.

The system was calibrated using both a short and a 50 Ω metal film resistor. The voltage noise of the entire system was found to be 1.2 nV/$\sqrt{\text{Hz}}$ at 1 kHz. To ensure that the bias current was not appreciably affecting the system, bias dependent measurements were done on the 50 Ω metal film resistor up to 1250 μA. The slope of the noise voltage spectrum for the system was found to be −0.94, giving a $1/f^2$ type power spectrum and a value at 1 Hz of 9×10^{-9} V/$\sqrt{\text{Hz}}$ regardless of bias. The value at 1 Hz was chosen as the figure of merit instead of the $1/f$ corner frequency to provide an easier comparison across experiments and to reduce the dependence on thermal noise of the device.

B. Bias dependence

Based on capacitance, differential resistance and responsivity, diodes with $X_{\text{InAlAs}}=20\%$ seem promising for sensitive zero-bias Schottky diode direct detectors operating in the millimeter- and submillimeter-wave bands.[3,9,10] To investigate the $1/f$ noise and low-frequency oscillations in this sample, measurements under different biasing conditions were taken (Fig. 1). A 100 μm mesa diode with a X_{InAlAs} $=20\%$ was measured at bias currents of 0, 24, 1250, and 40 000 μA.

Data taken with a bias current of 0 μA data represent the thermal noise of the diode plus the system noise, including $1/f$ noise from the LNA. Neither $1/f$ noise from the diode nor low-frequency oscillations are expected since both are current dependent. As the bias current is increased, the $1/f^2$ behavior of the noise spectrum is replaced by a $1/f$ behavior. This occurs not because the amplifier noise is changing character, but because the noise of the diode surpasses that of the system. By 1250 μA bias current, the diode noise dominates that of the system. The $1/f$ noise power was found to follow a 1.8 power-law dependence on the bias current even up to 40 mA, which is approaching the linear region of this particular diode. Using the bias dependent results, the $1/f$ voltage noise spectrum for a 20% InAlAs composition diode can be modeled as[11]

$$S_v = \frac{1.3 \times 10^{-10} i^{0.9}}{f^{0.5}}. \quad (1)$$

Bias dependent studies were also used to investigate the low-frequency oscillations, namely around 30 and 50 Hz. Here we find that at low current levels, 1250 μA and below, the 30 and 50 Hz peaks in the power spectral density follow a 1.9 power-law and 1.8 power-law dependence on bias current, respectively. It is unknown why the peaks deviate from this dependence as the bias is further increased and only a small increase in amplitude was seen with currents greater than 1250 μA.

C. Dependence on composition

In our previous work, the composition of the InAlGaAs was found to have a profound effect on the Schottky diode's electrical properties including the diode ideality, short-circuit responsivity, capacitance, and differential resistance.[3,9,10] In this work, we investigate the effect of composition on noise. The thermal noise will scale with resistance; however, the effect on $1/f$ noise and low-frequency oscillations is less obvious.

By changing the composition of the digital alloy, the band gap of the InAlGaAs, the Schottky barrier height, and the length of the depletion region also change. This has two important consequences: first, an increase/decrease in the depletion length causes more/fewer traps to efficiently participate in noise generation, and second, the relationship between the intrinsic Fermi level, conduction band edge, and trap energy levels may change.

This second point is especially important for the low-frequency oscillations. The oscillation frequency depends on the trap capture rate, emission rate, and the contact-to-contact spacing.[6] Since the trapping rate is strongly dependent on the energy separation between the trap and the conduction band, one would expect a constant rate for a trap that tracks the conduction band edge. For a trap that remains midgap, the rate should decrease with the increasing band gap. The amplitude of the oscillation may also be expected to change with the band gap.

The Schottky barrier height of these devices can be used to describe the energy difference between the conduction band and Fermi level at the junction. The Schottky barrier height has been shown to increase as the InAlAs fraction is increased.[3] If the trap tracks the conduction band, the difference between the Fermi level and the trap level at the junction changes with composition. Two general cases exist: the trap level is below the Fermi level ($E_f - E_t > 0$) at the junction [Fig. 2(a)], or the trap level is equal to or above the Fermi level ($E_t - E_f > 0$) [Fig. 2(b)]. When the trap level is below the Fermi level (first case) at the junction, we would expect the trap to have a small contribution to the noise for n-type devices since nowhere in the depletion region is $E_t - E_f \gg 0$. Therefore, the trap is typically occupied, and the electron capture rate is negligible everywhere in the active region. As the InAlAs composition is increased, the trap level will approach the Fermi level at the junction, assuming the trap tracks the conduction band. When $E_t - E_f \gg 0$, the trap should contribute very effectively to the noise because both the capture rate and emission rate are non-negligible. In the second case, $E_t - E_f \gg 0$, will always be satisfied somewhere in the depletion region. The expected composition dependence on the low-frequency oscillations is that the oscillation amplitudes will increase with the increasing Schottky barrier height until the trap level and Fermi level are coincident at the junction. Then, only a slight increase in the amplitude from increasing the composition is expected. This is

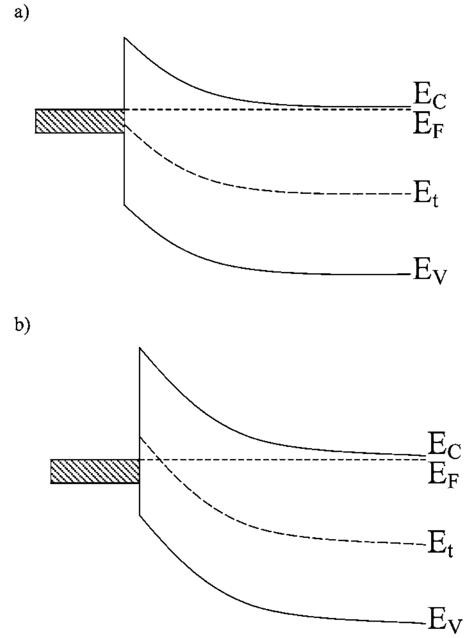

FIG. 2. Band diagrams for a Schottky diode with a trap energy (a) below and (b) above that of the Fermi energy at the junction.

due mainly to the increase in the depletion depth assuming the trap is distributed throughout the InAlGaAs.

Low-frequency noise was measured on 100 μm diodes with InAlAs composition fractions of 0%, 10%, 20%, 30%, 80%, and 100% with bias currents of 1240 μA in the forward direction. The most prominent low-frequency oscillation peaks observed, to the nearest 5 Hz, were: 10, 20, 30, 40, 55, 100, and 140 Hz. The $1/f$ noise remained relatively constant throughout the composition range, so this will not be discussed in detail.

Figure 3 shows the compositional dependence of the low-frequency oscillation amplitudes. No value is given for the 10 Hz peak in either the 0% or 100% samples because the $1/f$ noise was too high in these samples for an accurate measurement.

There are three distinct regions in the plot of oscillation amplitude versus composition: the flat region between 0% and 10%, the dramatic order of magnitude rise at 20% and the flat region from 30% to 100%. Assuming the trap respon-

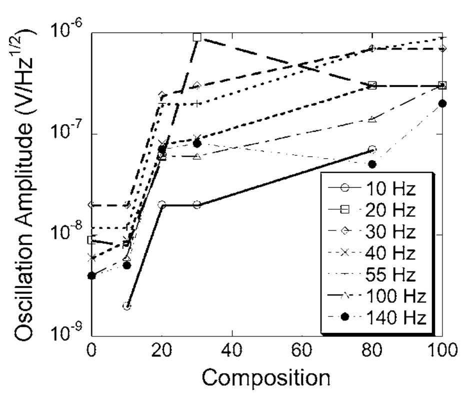

FIG. 3. Low-frequency oscillation amplitudes vs material composition (percentage of InAlAs) for ErAs contacted diodes at 10, 20, 30, 40, 55, 100, and 140 Hz.

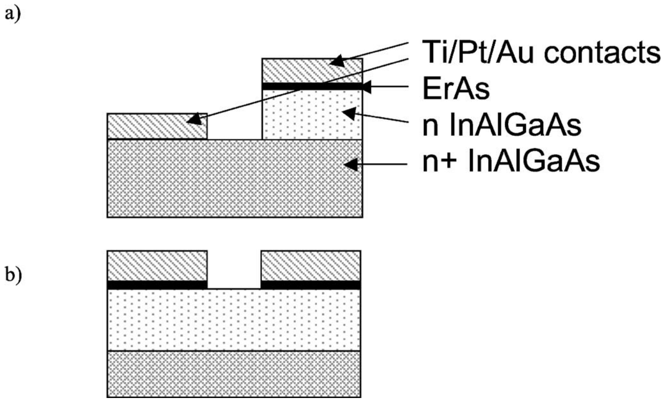

FIG. 4. Cross sections of a mesa diode (a) with sidewalls and (b) without sidewalls.

sible for these low-frequency oscillations tracks the conduction band, this behavior is consistent with the earlier discussion. In the terms of the early discussion, the 0% and 10% samples would be case 1 ($E_f - E_t > 0$), while the 30% to 100% samples would be case 2 ($E_t - E_f > 0$). The trap level and Fermi level at the junction coincide near the barrier height of the 20% sample, giving a conduction band/trap energy separation of approximately 200 meV. Johnstone of Semetrol used both $I-V-T$ and deep level transient spectroscopy to confirm the presence of a trap level between 200 and 210 meV. The identity of this trap is still under investigation but may be Er incorporated in the InAlGaAs and the trap energy of 200–210 meV corresponds well with the trap energy of 290 meV for Er in GaAs.[12]

D. Sidewall effect

To further investigate the noise sources in ErAs:InAlGaAs Schottky diodes, samples were made to study other possible mechanisms, such as the bottom Ohmic contacts and mesa sidewalls. The Ohmic contact consisted of a Ti/Pt/Au metallization fabricated directly on the n^+ InGaAs layer. The measured noise was well below that of the system, indicating that the contacts were not a significant source of noise. The same was true when contacts were made to a continuous Al/ErAs layer. To investigate sidewall noise, back-to-back Schottky diodes were fabricated with and without sidewalls (Fig. 4). The sample without sidewalls has the top n-InAlGaAs layer exposed, so some $1/f$ noise due to oxidation is expected. Comparing samples with and without sidewalls [Figs. 5(a) and 5(b)], and adjusting for sidewall area and current density, we find that >90% of the $1/f$ noise in the ErAs:InAlGaAs diodes can be attributed to the sidewalls. From these test samples, we also see that the source of the low-frequency oscillations appears to be in the bulk. This also indicates that these are due to defects/impurities in the InAlGaAs.

E. Aluminum contacted Schottky

In addition to the bias, composition, and sidewall investigations, a comparison was done between the ErAs:InAlGaAs diode and an Al:InAlGaAs diode, both from the same wafer and having a 20% InAlAs fraction. The aluminum

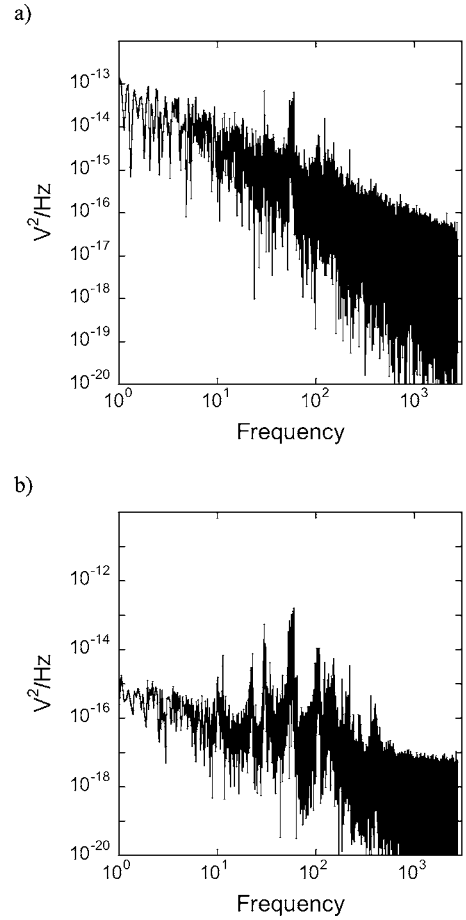

FIG. 5. Low-frequency noise spectrum for a 20% InAlAs composition ErAs contacted diode (a) with sidewalls and (b) without sidewalls.

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 ten times higher $1/f$ noise than the ErAs diode for comparable current densities, but still average for an aluminum Schottky diode (Fig. 6).[13] The low-frequency oscillations are also present in the aluminum Schottky sample with similar amplitudes, further supporting the theory that they are due to a trapping process in the bulk and not the junction itself.

V. CONCLUSIONS

The low-frequency noise characteristics of ErAs:InAlGaAs diodes have been examined and indicate that low-

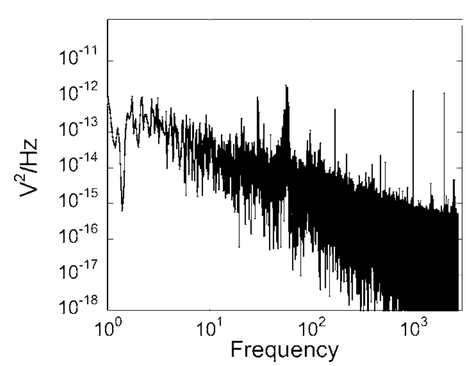

FIG. 6. Low-frequency noise spectrum for an aluminum contacted 20% InAlGaAs 100 μm mesa diode with 1240 μA of bias current.

$1/f$-noise Schottky junctions can be fabricated. The sidewalls have been shown to be the dominant $1/f$ noise source in these diodes. This becomes a bigger problem when scaling is considered because the sidewalls will become even more important (the sidewall area decreases more slowly than the anode area). However, with careful device design, and the use of surface passivation techniques, the sidewall noise should be reduced. One example of a possible device structure to minimize the contributions of the sidewalls to device noise is a double mesa structure where the semiconductor mesa is pushed away from the anode contact, and the majority of the current. Provided the Ohmic contacts are still placed close enough as to not add appreciable series resistance, this structure should be a viable high-frequency device.

The presence of low-frequency oscillations have also been observed and are traced to defects in the bulk, most likely Er related defects with a trap energy of ~200–210 meV below the conduction band.

The low $1/f$ noise behavior shown here, coupled with the good ideality factor and the inherent tunability of the ErAs:InAlGaAs system makes these diodes a promising choice for high-frequency direct detection. The low $1/f$ noise also makes these devices attractive for other applications, most notably mixers where the high drive powers tend to bias the device into regimes where $1/f$ noise becomes large in typical devices.

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