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A GaAs acoustic sensor with frequency output based on resonant tunneling diodes

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Abstract

This paper reports a novel acoustic sensor with a frequency output based on AlAs/$In_xGa_{1-x}As$/GaAs resonant tunneling diode (RTD). The RTD is incorporated in a 1 μm thick membrane and the fabrication technology of the membrane is based upon the selective etch of GaAs with AlAs as an etch stop layer. A relaxation oscillator is obtained with the RTD biased in the negative differential resistance (NDR) region. Acoustic pressure applied to the RTD changes the frequency of oscillation due to the shift in current–voltage characteristics. The main feature of this sensor type is the direct frequency output, which is linearly dependent on pressure, and the linear sensitivity can be up to 21 kHz/kPa.

Keywords: GaAs; Acoustic sensor; RTD; Etch-stop technology

1. Introduction

In recent years, extensive research on resonant tunneling diodes (RTDs) has been dominated by the needs of semiconductor heterostructure devices for high frequency operation and high speed applications. Oscillations of up to 712 GHz have been reported and several applications of RTDs for multivalued logic have been proposed [1–3]. However, the RTD current–voltage characteristics are very sensitive to pressure [4] and temperature changes [5], mainly in the negative differential resistance region.

An acoustic sensor is an electro-mechanical-acoustic transducer that transforms acoustic energy into electrical energy. Although many different transduction principles have been employed [6], all are based on the detection of a pressure-induced structural deflection. In order to make a sensitive acoustic sensor, a deformable membrane is used to amplify the externally applied pressure. In the work, a membrane with an incorporated resonant tunnelling structure is constructed. The pressure will bend the membrane and introduce strain in the layers of the resonant tunnelling structure. The strain will induce the change of the position of the energy states in the quantum well, which modifies the current–voltage characteristics of the RTD. If an oscillating RTD was used, very small pressures could be measured as a shift in oscillation frequency [7]. At last, the RTD will transform this pressure into an electrical frequency signal.

2. The design of the acoustic sensor

The acoustic sensor transforms acoustic energy into electrical energy by transducing the strain on the top surface of a deflected membrane, which is deformed by the acoustic pressure, into a corresponding change in oscillation frequency of RTD. The cross-section of the acoustic sensor is shown in Fig. 1. The device consists of a circular low stress undoped GaAs membrane, a hard back plate with a back vent and the RTDs with air-bridge electrode.

2.1. Sensitivity analysis

For a clamped, circular disk of radius a and thickness h, under a uniform in-plane stress, $\sigma_0 = N_0/h$ and a uniform transverse pressure load, p_z. For the case of small-deflection theory, the equilibrium equations for symmetric bending reduce to a

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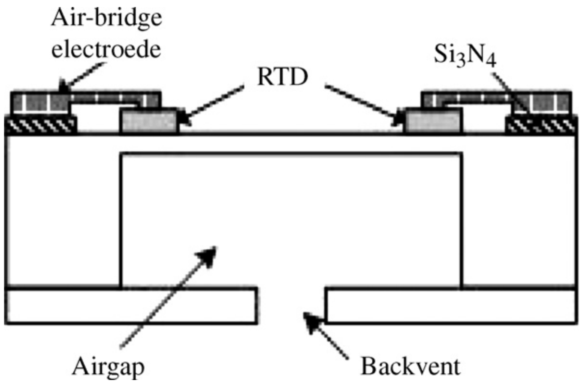

Fig. 1. Cross-section of the acoustic sensor.

modified Bessel equation for the slope, $\phi(r)$ [8]:

$$r^2\frac{d^2\phi}{dr^2}+r\frac{d\phi}{dr}-\left[1+k^2\left(\frac{r}{a}\right)^2\right]\phi=6(1-\nu^2)\frac{p_z r^3}{Eh^3} \quad (1)$$

where E is the modulus of elasticity, ν the Poisson's ratio and k is the tension parameter defined as [8]

$$k=\frac{a}{h}\sqrt{\frac{12(1-\nu^2)\sigma_0}{E}} \quad (2)$$

The expressions for the radial stress on the top side of the membrane are given by Hooke's Law [8]:

$$\sigma_r=\frac{3p_z a^2}{h^2}\left[\frac{\nu+1}{k^2}-\frac{I_0(kr/a)}{kI_1(k)}-\frac{a(\nu-1)I_1(kr/a)}{rk^2I_1(k)}\right] \quad (3)$$

And for $k>20$, the mechanical sensitivity S_m may be approximated using the large value approximations for the modified Bessel functions [9],

$$S_m=\lim_{k\to\infty}\frac{\sigma_r(r)}{p_z}=\frac{3a^2}{h^2k^2}\left[(\nu+1)-\frac{((kr/a)-1+\nu)}{(r/a)^{3/2}}\ e^{-k(1-(r/a))}\right] \quad (4)$$

The above solution represents the membrane solution (first term) plus a small exponential correction (second term) to accommodate the zero slope condition at the clamped edge.

2.2. Acoustic characteristics analysis

The acoustic characteristics of the acoustic sensor determine the low-frequency cut-on frequency, diaphragm damping and the overall sensitivity. The frequency response of the acoustic sensor can be calculated using the equivalent analog electrical network of Fig. 2 [8].

In this model, the distributed deflection of the diaphragm is lumped into a rectilinear piston possessing an effective mass (M_{me}) and compliance (C_{me}). In addition, this model incorporates the acoustic impedance due to the cavity compliance (C_a), vent mass (M_a) and dissipation (R_a) and diaphragm radiation mass (M_{rad}). In this electro-acoustic analogy: voltage is replaced

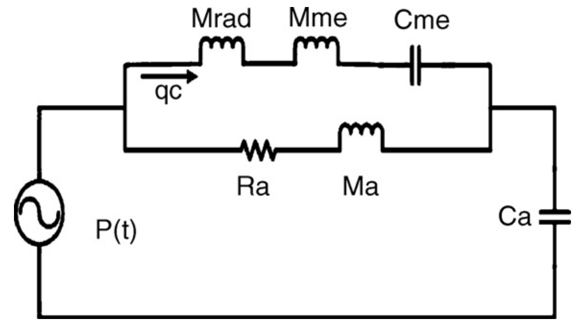

Fig. 2. Equivalent electrical circuit of the acoustic sensor.

by pressure, $p(t)$ and current by volume velocity, $q(t)$. The acoustic sensitivity is $qc(w)/jwp(w)$. And in the Laplace domain, the normalized transfer function $H(s)$ for the acoustic sensor model is given below [8]

$$H(s)=\frac{(R_a+sM_a)(sC_{mea}C_a/A)}{s(R_a+sM_a)(s^2M_{mea}C_{mea}+1)C_a+s^2M_{mea}C_{mea}+1+s(R_a+sM_a)C_{mea}} \quad (5)$$

The sensitivity of the acoustic sensor is hence a function of the frequency. And this model predicts the low frequency cut-on, the flat response for the operating range and the system resonance of the acoustic sensor.

In our work, the structure dimension of the acoustic sensor is: the thickness and radius of the membrane is $h=1\ \mu m$, $a=0.5mm$, respectively, the height of the air gap is $h_{cav}=100\mu m$, the thickness of the back plate is $L=1mm$ and the hydraulic diameter of the vent $d_{vent}=20\ \mu m$. Using the above values, the calculated frequency response of the acoustic sensor is shown in Fig. 3. It is satisfied with the demand of frequency response (20 Hz to 20 kHz). And the mechanical sensitivity S_m of the acoustic sensor structure is up to 23 K.

3. The process of the acoustic sensor

To construct micromechanical structures in a AlAs/$In_xGa_{1-x}As$/GaAs material system, the selective etching char-

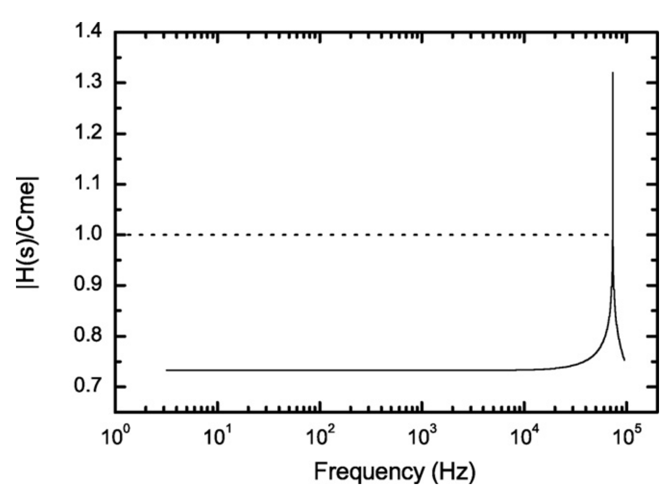

Fig. 3. Theoretical frequency response of the acoustic sensor.