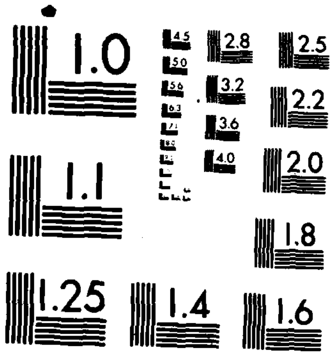
AD-A162 068   ANALYTICAL INVESTIGATIONS OF BULK WAVE RESONATORS IN   1/1
THE PIEZOELECTRIC TH (U) RENSSELAER POLYTECHNIC INST
TROY NY DEPT OF MECHANICAL ENGINE   H F TIERSTEN
UNCLASSIFIED 30 SEP 85 AFOSR-TR-85-1042 AFOSR-84-0351   F/G 9/5   NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

②

Annual Report on Analytical Investigations of Bulk Wave Resonators in the Piezoelectric Thin Film on Gallium-Arsenide Configuration

Harry F. Tiersten

September 1985

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- [illegible]

6a. NAME OF PERFORMING ORGANIZATION: Rensselaer Polytechnic Institute

6b. OFFICE SYMBOL *(If applicable)*

6c. ADDRESS *(City, State and ZIP Code)*:
Department of Mechanical Engineering,
Aeronautical Engineering & Mechanics
Troy, NY 12180-3590

7a. NAME OF MONITORING ORGANIZATION: Air Force Office of Scientific Research

7b. ADDRESS *(City, State and ZIP Code)*:
Bolling Air Force Base
Bldg. 410

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office of Scientific Research

8b. OFFICE SYMBOL *(If applicable)*: NE

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Grant No. AFOSR-84-0351

8c. ADDRESS *(City, State and ZIP Code)*:
Bolling Air Force Base
Bldg. 410

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2306	B2	

11. TITLE *(Include Security Classification)*: (over)

12. PERSONAL AUTHOR(S): Harry F. Tiersten

13a. TYPE OF REPORT: Annual

13b. TIME COVERED: FROM 9/1/84 TO 8/31/85

14. DATE OF REPORT *(Yr., Mo., Day)*: 1985, September 30

15. PAGE COUNT: 9

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Piezoelectricity; Elasticity; Resonators; Bulk Waves; Thin Films; Semiconductor Wafers; Composite Resonators; Energy Trapping; Radiation; Quality Factor; Plate Vibrations ~~(over)~~

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Trapped energy modes in the piezoelectric thin film on semiconductor composite resonator are explained and contrasted with modes that do not trap energy. The results of calculations of the quality factor of the fundamental essentially thickness-extensional mode in the composite resonator due to radiation into the bulk semiconductor wafer are discussed. The calculations were performed for two configurations of the composite resonator in which the mode is not trapped and for a configuration in which the mode is trapped. The combination of materials was aluminum-nitride on gallium-arsenide. The calculations show that when trapping is not present the quality factor is a very rapidly varying function of the ratio of the composite resonator thickness to the wafer thickness and that the range of variation is very large, i.e., between one and two orders of magnitude. The calculations also reveal that when trapping is present the quality factor is always much larger and its range of variation with thickness ratio much smaller than when trapping is not present.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Kevin J. Malloy

22b. TELEPHONE NUMBER *(Include Area Code)*: (202) 767-4931

22c. OFFICE SYMBOL: NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

11. "Analytical Investigations of Bulk Wave Resonators in the Piezoelectric Thin Film on Gallium-Arsenide Configuration"

18. Forced Vibrations; Dispersion Relations; Variational Approximation; Thickness Extensional Vibrations; Gallium-Arsenide; Aluminum-Nitride

The composite resonator consists of a uniform thin layer etched in a small well-defined region of a semiconducting wafer to form a diaphragm, upon which is deposited a thin piezoelectric film along with the electrodes to form a resonant region directly on the wafer. Under this program the case of the aluminum-nitride film on gallium-arsenide is investigated.

The accuracy of the values of the material constants of aluminum nitride that appear in the literature[1] is open to some question. The reason for this is that the published value of the elastic constant c_{33}, which is the constant that determines the pure thickness-extensional resonant frequencies, yields thickness-extensional resonant frequencies that differ by 24% from other measured thickness-extensional resonant frequencies appearing in the literature[2]. Nevertheless, the published[1] values of the elastic constants have been used in all calculations reported here.

Before proceeding with a discussion of our recent work, it is essential for clarity that we briefly explain the meaning of the words "energy trapping." Since the pure thickness-extensional resonant frequencies are cutoff frequencies, there is usually a nearby frequency range in which the transverse mode shape is evanescent. There is also a nearby frequency range in which the transverse mode shape is trigonometric. Consequently, by the selection of the appropriate thickness-extensional overtone (or fundamental) and/or the appropriate adjustment of the geometry in the electroded and unelectroded regions, the transverse modal behavior can be made to decay with distance away from the electrodes in the unelectroded region. The resulting vibration is called a trapped energy mode, which radiates a controllably small amount of energy into the adjacent thick portion of the semiconducting wafer and, hence, results in the highest possible Q, albeit with many nearby spurious modes with high Q. Alternatively, the overtone and/or geometry can be selected so that the mode does not decay with distance away from the electrode in the unelectroded region and the resulting vibration is not a trapped energy mode. In this case much more energy is radiated into the adjacent thick portion of the semiconducting wafer and much lower Q's result. Although there are still many nearby spurious modes, they are less troublesome because the Q's are lower. All experimental work on the composite resonator reported to date has been for this latter case. On the other hand a detailed analytical treatment of the composite resonator for the case when trapping is present appears in the literature[3] along with a detailed discussion of when trapping is and is not present.

Using the aforementioned constants of aluminum-nitride, we have found that the fundamental essentially thickness-extensional mode will not trap for an aluminum-nitride film on a gallium-arsenide diaphragm in the flat plate configuration. However, the fundamental mode will trap if the gallium-arsenide diaphragm is appropriately notched a small amount in the electroded region, as shown in Fig. 9 of Ref. 3. In addition, we have found that the second essentially thickness-extensional mode will trap for the same film and substrate materials in the flat plate configuration for any ratio of film-thickness to diaphragm-thickness.

An analysis of the vibrations of a composite resonator, which is driven by the application of an a.c. voltage across strip electrodes on the major surfaces of the film, has been performed. The analysis includes the pertinent waves in the active region of the composite resonator, as well as all radiating waves in the thick gallium-arsenide plate. The solution is obtained by satisfying the differential equations for the piezoelectric film and semiconductor as well as all boundary conditions on the major surfaces of the film and semiconductor exactly and using the appropriate variational principle to satisfy the remaining conditions along the minor interfaces approximately. The minor interfaces separate the electroded from the unelectroded regions of the resonator and the thin region of the gallium-arsenide from the thick region. Past experience shows that this type of approximation yields extremely accurate results if all the proper waves are included. Both the configuration in which the film ends at the edges of the electrodes and in which it continues to the edges of the etched diaphragm have been considered when trapping is not present, along with the latter configuration when trapping is present. In each instance the Q at the resonance condition has been calculated.

In performing the aforementioned calculations we have found that it is imperative that all radiating plate waves in the thick region of the gallium-arsenide be included in order to achieve accuracy. Since at a given frequency the number of radiating waves in a plate goes up significantly with thickness, we have considered gallium-arsenide wafers no thicker than 8 mils at a frequency around 132 MHz, for which there are 30 radiating plate waves. Specifically, calculations have been performed for thicknesses ranging from 1.5 to 8 mils. The 1.5 mil case was considered at an early stage in the calculations to check the program with as small a number of dispersion curves as possible. All the definitive calculations were for a film thickness of 7 microns and a diaphragm thickness of 14 microns and the lateral dimensions were adjusted slightly to maintain the same resonant frequency for computational convenience. The major calculations were performed for wafer thicknesses ranging from 4 mils to 8 mils because this is considered to be within the practical range. The calculated Q is a very rapidly varying function of the wafer thickness. Consequently, calculations had to be performed for very small increments in thickness in order to get all the peaks and valleys in the interval.

In the absence of trapping in the case in which the film ends at the edges of the diaphragm, the highest Q obtained is about 4000 and the lowest is about 10 and there are about 10 peaks for thicknesses between 4 mils and 8 mils. The highest valley has a Q of 700. The calculations were performed using an increment in thickness of 1 micron. In the case in which the film ends at the edges of the electrode, the highest Q calculated so far is about 14,000 and the lowest Q is about 200. At present this calculation is not quite complete. Calculations were performed when trapping was induced by notching the diaphragm under the electrode. As expected, the Q due to radiation can be made as high as we wish simply by extending the lateral dimensions of the film and diaphragm. We have calculated Q's higher than 200,000 for quite reasonable dimensions. In interpreting the foregoing information it should be remembered that the high Q's calculated should be higher than the actual Q's because the material Q and the Q due to radiation into the air are not included. The results discussed above mean that in order to obtain reasonably high Q when trapping is not present for a given wafer thickness, the thicknesses of the film and diaphragm must be very precisely selected.

References

1. K. Tsubouchi, K. Sugai and N. Mikoshiba, "AlN Material Constants Evaluation and SAW Properties on AlN/Al_2O_3 and AlN/Si," 1981 Ultrasonics Symposium Proceedings, IEEE Cat. No. 81 CH1689-9, Institute of Electrical and Electronics Engineers, New York (1981), p. 375.

2. J. S. Wang, Y. Y. Chen and K. M. Lakin, "Reactive Ion Etching of Piezoelectric Films for Acoustic Wave Devices," 1982 Ultrasonics Symposium Proceedings, IEEE Cat. No. 82 CH1823-4, Institute of Electrical and Electronics Engineers, New York (1982), p. 346.

3. H. F. Tiersten and D. S. Stevens, "An Analysis of Thickness-Extensional Trapped Energy Resonant Device Structures with Rectangular Electrodes in the Piezoelectric Thin Film on Silicon Configuration," J. Appl. Phys., 54, 5893 (1983).

A talk entitled "On the Reduction in Quality Factor of the Piezoelectric Thin Film on Semiconductor Composite Resonator Due to Radiation into the Bulk Semiconductor" by D. S. Stevens, H. F. Tiersten and D. V. Shick is to be presented at the upcoming 1985 Ultrasonics Symposium in mid-October. A paper with the same title is to be published in the 1985 Ultrasonics Symposium Proceedings. The abstract of the talk is appended to this report.

ON THE REDUCTION IN QUALITY FACTOR OF THE PIEZOELECTRIC THIN FILM ON SEMICONDUCTOR COMPOSITE RESONATOR DUE TO RADIATION INTO THE BULK SEMICONDUCTOR

D. S. Stevens, H. F. Tiersten and D. V. Shick, Rensselaer Polytechnic Institute, Troy, NY 12181.

The composite resonator consists of a uniform thin layer etched in a small well-defined region of a semiconductor wafer to form a diaphragm, upon which is deposited a thin piezoelectric film along with the electrodes to form a resonant region directly on the wafer. Although the composite resonator, which operates in an essentially thickness-extensional mode, can be constructed to employ energy trapping, all existing experimental work in the literature is for the case when trapping is not present. All previous analytical work expressly ignores radiation into the bulk semiconductor except one treatment, which unrealistically ignores the junction between the etched diaphragm and the bulk semiconductor. In this work an analysis of the composite resonator driven into essentially thickness-extensional vibrations by the application of a voltage to strip electrodes is performed. The analysis includes all pertinent waves in the active region of the composite resonator as well as all radiating plate waves in the thick portion of the semiconductor. The solution consists of a sum of terms satisfying all differential equations and boundary conditions on major surfaces exactly and uses the appropriate variational principle of linear piezoelectricity to satisfy the remaining conditions across minor interfaces approximately. For the case of the aluminum-nitride film on gallium-arsenide the Q is calculated for both the configuration in which the film ends at the edges of the electrodes and in which it continues to the edges of the etched diaphragm when trapping is not present and for the latter configuration when trapping is present.

Supported in part by AFOSR under Grant. No. AFOSR-84-0351.

H. F. Tiersten
Department of Mechanical Engineering,
Aeronautical Engineering & Mechanics
Rensselaer Polytechnic Institute
Troy, NY 12181
Telephone: (518) 266-6766

END

FILMED

1-86

DTIC