A Voltage-Controlled Tunable Thin-Film Distributed RC Notch Filter

Won-Youl Choi and Susan Trolier-McKinstry, *Member, IEEE*

***Abstract*—Notch filters are widely used in communication and instrumentation systems not only for eliminating undesired frequencies and for measuring transient harmonic distortions, but also as central components of selective filters and oscillators in feedback arrangements. This paper describes the characteristics of a thin-film distributed RC (DRC) notch filter made from Au/TaN/Y-doped $BaTiO_3$ (Y-BT)/Pt. The dielectric (Y-BT) and resistive (TaN) films were grown by pulsed laser deposition (PLD). A notch frequency of 2.8 MHz and notch depth of −76.7 dB were measured from zero with a notch resistance (R_N) of 34 Ω. The experimental optimum notch parameters of $\alpha = R/R_N = 19.7$ and $x_n = \omega/\omega_o = 33.0$ were obtained. Tunability of the notch frequency was observed with an applied dc bias voltage.**

***Index Terms*—$BaTiO_3$ thin film, pulsed laser deposition, RC notch filter, TaN thin film, Y-doping.**

I. INTRODUCTION

THE USE of distributed-RC (DRC) rather than lumped-RC (LRC) networks as frequency-selective elements in hybrid integrated-circuit active filters has been advocated as offering the practical advantages of increased simplicity and reliability [1]. For example, Kaufman [2] and Kaufman and Garrett [3] studied a notch filter consisting of an RC transmission line fabricated on a semiconductor substrate in conjunction with a lumped resistance and described the effect of geometrical tapering on the characteristics of DRC substrates. Su [4] reported an RC filter with staggered notch frequencies fabricated using Teledetos paper and Myler film as the resistive and dielectric films, respectively. Ahmad and Singh [5] fabricated a thin film uniformly DRC structure consisting of Al/Al_2O_3–SiO/Ni–Cr films using vacuum evaporation. The electrical performance of uniformly DRC notch networks fabricated using conventional integrated circuit (IC) thin-film vacuum deposition techniques and a very large scale integration (VLSI) interlevel silicon dioxide spin-on glass (SOG) dielectric planarization material was reported by Kolesar [6].

For such a filter, the optimum null in the open-circuit voltage-transfer function is obtained for a particular ratio of the resistors, and the frequency of the null is then determined by the RC product. Hence, if the capacitance of the distributed section could be changed without changing the resistance, an ideal tuning situation would exist. Swart and Campbell [7] proposed a thin film device with metal1–insulator–semiconductor–metal2 (MISM) structure in which the capacitor provided a voltage-variable capacitance. Also, Wong [8] produced a voltage-tunable RC notch filter using silicon-on-sapphire technology. A linear voltage-tunable distributed null device has been fabricated and studied by Benz and Mattauch [9]. Some tunable RC notch filters using monolithic microwave integrated circuit technology and printing processes have also been reported [10], [11].

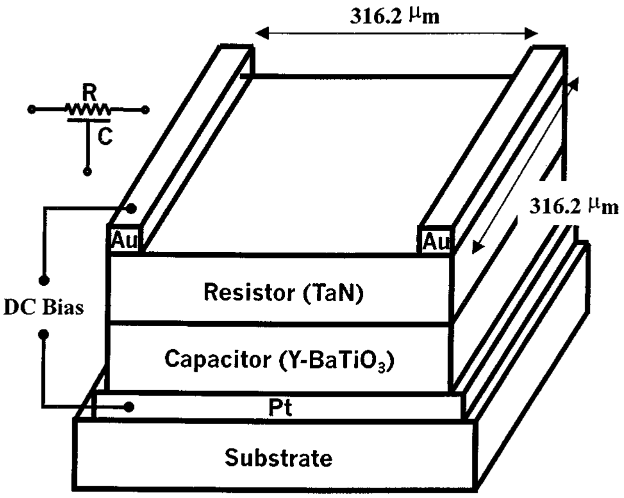

Fig. 1. Distributed RC network structure.

In this work, the properties of a thin film uniformly distributed RC (DRC) network based on Au/TaN/Y-doped $BaTiO_3$ (Y-BT)/Pt films were studied. The Y-doped $BaTiO_3$ films have better crystallinity, smaller grain sizes, higher dielectric constants, and lower losses than Y-free ones for the some deposition conditions [12]–[14]. In bulk ceramics, Y-doping also improves long-term reliability under dc fields. Because TaN films can withstand high temperatures and have stable resistivity values [15], [16], it has been used as a resistive film in active silicon integrated circuits and hybrid microwave integrated circuits. The distributed capacitance and resistance of this RC network was examined with respect to frequency and temperature, respectively. The behavior of this structure as a tunable notch filter using a voltage-variable capacitance with various lumped-notch resistances and dc bias voltages was investigated experimentally (see Fig. 1).

II. EXPERIMENTAL PROCEDURE

The dielectric and resistive thin films for the DRC networks were prepared by pulsed laser deposition (PLD). Y-doped $BaTiO_3$

Manuscript received July 25, 2000; revised November 3, 2000. This work was supported by the TDK Cooperation. This paper was recommended for publication by Associate Editor A. Deutsch upon evaluation of the reviewers' comments.

W.-Y. Choi is with the MEMS Laboratory, S&C Sector, Samsung Advanced Institute of Technology, Suwon 440–600, Korea.

S. Trolier-McKinstry is with the Materials Research Laboratory, Pennsylvania State University, University Park, PA 16802 USA.

Publisher Item Identifier S 1521-3331(01)01381-2.

TABLE I

PULSED LASER DEPOSITION PARAMETERS FOR DIELECTRIC (Y-BT) AND RESISTIVE (TaN) FILM GROWTH

Components	Dielectric Film (Y-doped $BaTiO_3$)	Resistive Film (TaN)
Base Pressure	< 3 X 10^{-6} Torr	< 3 X 10^{-6} Torr
Targets	$BaTiO_3$ Ceramics (Ba/Ti = 50.1/49.9) (0.2wt% Y_2O_3, 0.2wt% MnO_2, 0.1wt% SiO_2)	Ta Metal (99.95% purity)
Deposition Temp./Time	700 °C / 20min	300 °C / 45min
Atmosphere /Working Pressure	N_2 gas / 100 mTorr	N_2 gas / 100 mTorr
Laser Frequency/Fluence	10 Hz / 4.2 J/cm^2	20 Hz / 3.1 J/cm^2
Substrate Structure	Pt/Ti/SiO_2/Si	SiO_2/Si or Y-BT/Pt/Ti/SiO_2/Si
Target-Substrate Distance	6 cm	8 cm

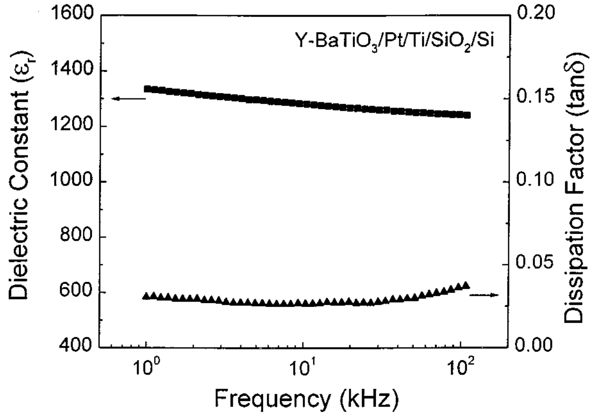

Fig. 2. Dielectric constants and dissipation factors (tanδ) of the dielectric (Y-BT) film as a function of frequency.

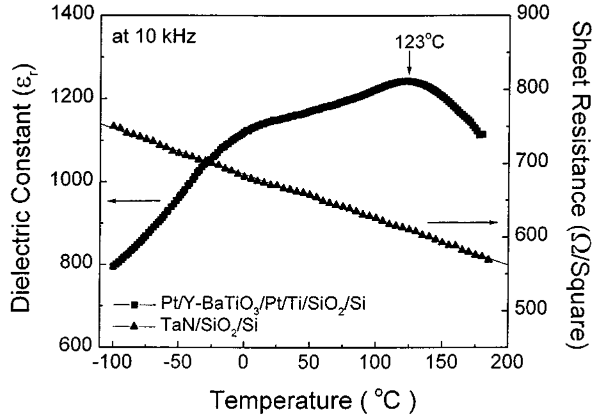

Fig. 3. Permittivity of the Y-BT dielectric film and sheet resistance of the TaN resistive film as a function of temperature.

(Y-BT) and TaN film were used as the dielectric and resistive films, respectively. The specific deposition parameters are given in Table I. Y-BT and TaN films were grown in pure (99.99%) N_2 atmospheres from 0.2wt% Y_2O_3 doped $BaTiO_3$ ceramic and a 99.95% pure Ta metal target, respectively. Pt/Ti/SiO_2/Si substrates were used. In both cases, a 10 $\sim$ 20 Hz pulsed laser repetition frequency with an energy density of 3.1 $\sim$ 4.2 J/cm^2, and a working pressure of 100 mtorr were found to yield good film properties. Growth temperatures spanning 300 °C to 700 °C were achieved by adhering the substrates to a stainless steel block-style heater with silver paint. The growth temperature for the TaN film was deliberately kept low to minimize reaction with the underlying capacitor film. A Lambda Physik Compex 102 excimer laser operating at 248 nm was used. The top electrode (Au) film was deposited at room temperature by dc sputtering. Top electrode patterns with a $\sim$1200 Å thickness were fabricated by photolithography and wet etching processes.

The crystallinity of the Y-BT and TaN films was examined with an X-ray diffractometer using Cu K_α radiation (Scintag, Inc.). The dielectric constants and dissipation factors (tanδ) of the Y-BT films were measured using a HP4194A impedance analyzer with a 0.03 V oscillation level or HP 4284A LCR meter. The sheet resistance of the TaN films on the SiO_2/Si substrates were measured as a function of temperature using a four-point probe and a Fluke 8840A multimeter. A computer controlled Delta Design oven was used to control the temperature between -100 °C and 200 °C.

Following the fabrication of the notch filters, the surface and cross-sectional morphologies of the layers were observed with optical microscopy and scanning electron microscopy (SEM). The open-circuit voltage transfer function of the DRC notch filter was measured using the HP 4194A impedance analyzer. To satisfy the optimum null condition for the notch filter, a variable resistance lumped-notch resistor was used. Tunability was examined with various notch resistances (R_N) and the dc bias voltages generated by the HP4192A impedance analyzer.

III. RESULTS AND DISCUSSION

Fig. 2 shows the dielectric constants (ε_r) and dissipation factors (tanδ) of Y-BT films on Pt/Ti/SiO_2/Si substrates as a function of frequency. In order to measure the dielectric constants and dissipation factors (tanδ) of the Y-BT dielectric layers, 0.3 mm diameter Pt top electrodes were sputtered through a shadow mask onto the top surface of the films. Dielectric constants of 1240 $\sim$ 1330 and dissipation factors (tanδ) of 0.03 at 1 kHz were observed. The temperature dependence of the permittivity for Y-BT films as well as the sheet resistance of TaN films (on SiO_2/Si substrates) are shown in Fig. 3. The dielectric constant at room temperature and the Curie point at 10 kHz are 1150 and 123 °C, respectively. The high temperature dielectric data were fitted to the Curie–Weiss model (the

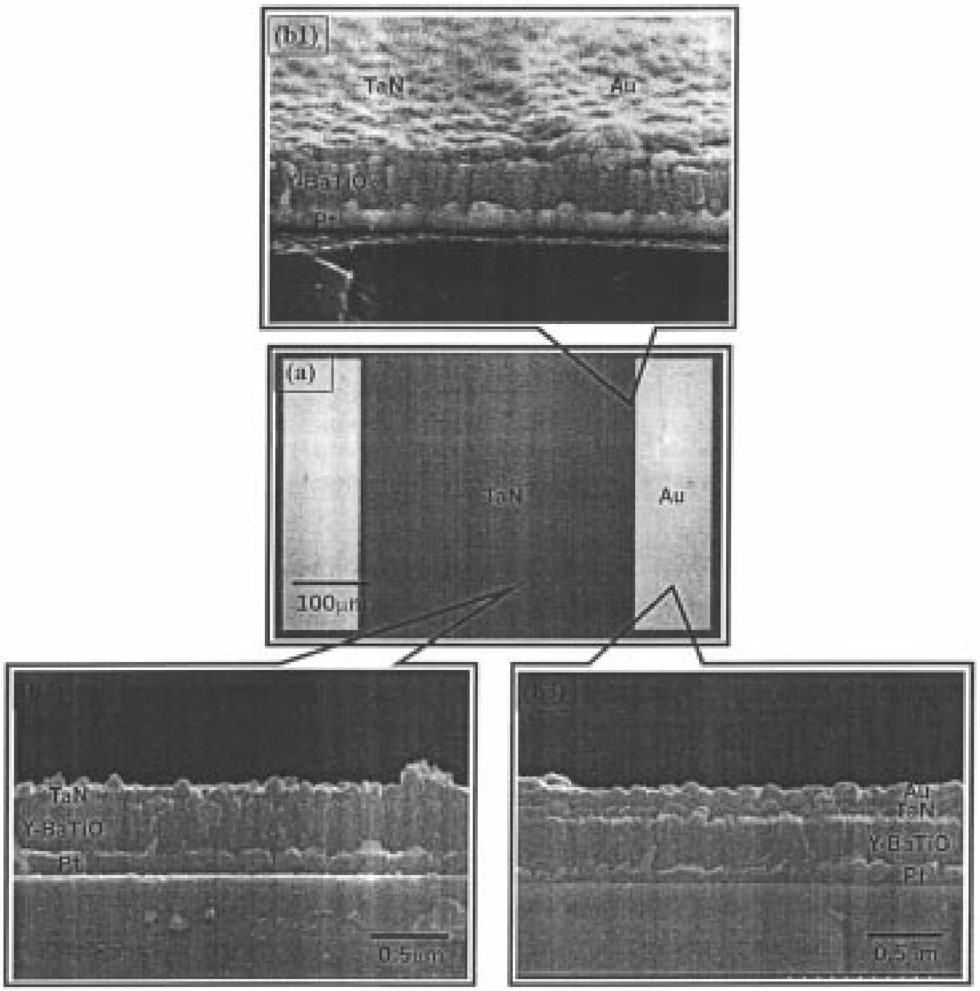

Fig. 4. (a) Surface optical microscopy image and (b) cross-sectional SEM images of distributed RC network.

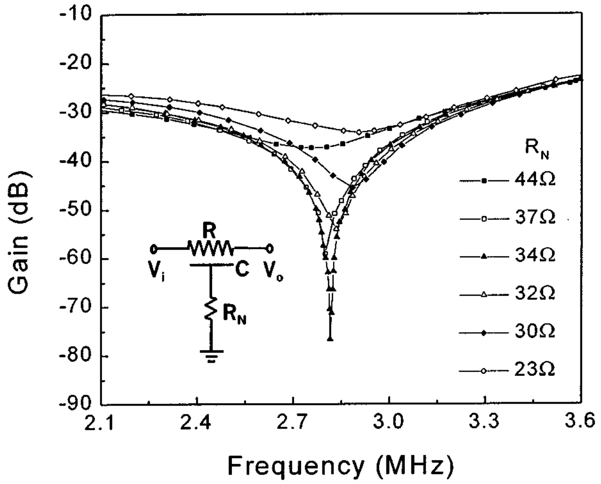

Fig. 5. Measured open-circuit voltage transfer function of the fabricated DRC network for various notch resistances (R_N).

linear relationship between the inverse dielectric constant and temperature above the ferroelectric transition) [17]

$$\varepsilon_r - 1 = \frac{C}{(T - T_O)} \tag{1}$$

where

C Curie constant;
T absolute temperature;
T_0 Curie temperature.

The Curie constant was calculated from the high temperature data. The Curie constant is on the order of 10^5 K^{-1}. The sheet resistance of the TaN film at room temperature (20 °C) is 670 Ω, and the temperature coefficient of resistance (TCR) is -920 ppm/°C.

Fig. 4 shows SEM micrographs of the top surface and cross-sections of the distributed filter structure obtained by photolithography and wet etching of the Au top electrode. Good top electrode patterns for uniformly DRC networks were obtained. The thicknesses of the dielectric Y-BT film and resistive TaN film were ~ 3800 Å and ~ 1200 Å, respectively. From the thicknesses and effective area (316.2 μm × 316.2 μm) of the dielectric and resistive films, a distributed capacitance of 2.8 nF and resistance of 670 Ω were calculated, assuming no reaction layers between the films.

It has been shown [18] that the open circuit voltage transfer function, T, of a uniformly DRC notch filter with dielectric dissipation is given by

$$T = \frac{V\mathrm{out}}{V\mathrm{in}} = \frac{\alpha + \gamma \sinh \gamma}{\alpha \cosh \gamma + \gamma \sinh \gamma} \tag{2}$$

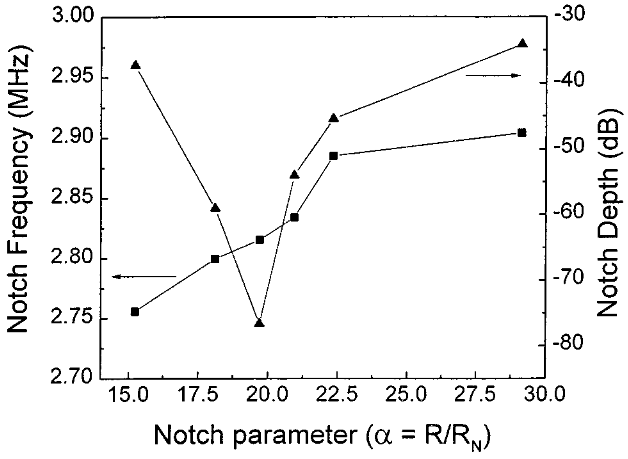

Fig. 6. Notch frequency and depth with notch parameters ($\alpha = R/R_N$).

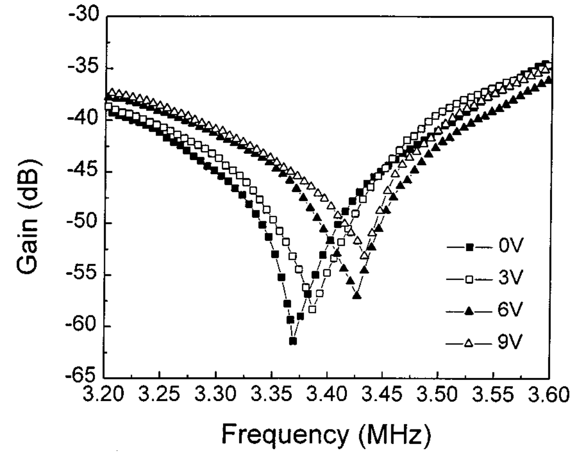

Fig. 7. Measured open-circuit voltage transfer function of the fabricated DRC network for various dc bias voltages.

where $\gamma = [jx/\{1+jxB(x)\}]^{1/2}$ is expressed in terms of a frequency normalization parameter $x = \omega/\omega_o$ and a frequency dependent normalized dielectric dissipation factor $B(x)$. In these relationships $\omega_o = 1/(RC)$, where R and C, respectively, denote the distributed resistance and capacitance of the structure. $B(x) = \tan\delta/x$, and the parameter (α) is given as $\alpha = R/R_N$ in terms of the lumped notch resistance (R_N). The zero of transmission in (2) that yields the optimum notch condition is realized when both the real and imaginary components of the numerator are zero. In particular, the optimum notch parameters for an ideal notch filter which is a lossless ($B = 0$) and free of parasitics are $\alpha = 17.786$ and $x_n = 11.19$.

In this work, the experimentally observed open-circuit voltage transfer function of the fabricated DRC notch filter is shown in Fig. 5 together with its circuit (having $R = 670\ \Omega$, $C = 2.8$ nF, and $f_o = (2\pi RC)^{-1} = 84.8$ kHz). The values found for the notch frequency and notch depth when $R_N = 34\ \Omega$ were 2.8 MHz and -76.7 dB, respectively. This gives the experimental optimum notch parameters $\alpha = R/R_N = 19.7$ and $x_n = \omega/\omega_o = 33.0$. The difference between the values of the notch parameters obtained experimentally and those predicted theoretically may be due to the dissipation factor (tanδ) of the dielectric film (Y-BT) and parasitics. In addition, it is possible that a tantalum oxide (TaO_x) with a low dielectric constant was unintentionally formed between the capacitor and the resistor during the nitride film growth. Any tantalum oxide phase present would decrease the total distributed capacitance of the RC network and causes the optimum notch frequency to shift to higher values.

The behavior of the notch filter with notch resistance (R_N) were observed. For $R_N = 23\ \Omega$, $30\ \Omega$, $32\ \Omega$, $34\ \Omega$, $37\ \Omega$, and 44 Ω, the notch frequencies obtained were 2.90 MHz, 2.88 MHz, 2.83 MHz, 2.82 MHz, 2.80 MHz, and 2.76 MHz, respectively. The variation of the notch frequency and depth with notch parameter ($\alpha = R/R_N$) is plotted in Fig. 6. The relatively high insertion loss of $\sim$ 20 dB may be due to the high resistance TaN film. A lower insertion loss could probably be achieved with a higher conductivity resistive film.

The notch filter could also be tuned with a dc bias voltage, independently of the distributed resistance. This is due to the field dependence of the dielectric constants of the Y-BT film. Fig. 7 shows the measured open-circuit voltage transfer function of a DRC network made with a thicker dielectric film (Y-BT) for various dc bias voltages. Fig. 8 shows the dielectric constant (ε_r) of a Y-BT film as a function of dc bias voltage. Given the decrease in the Y-BT film permittivity with field, the distributed capacitance should drop with increased dc bias voltage, and the

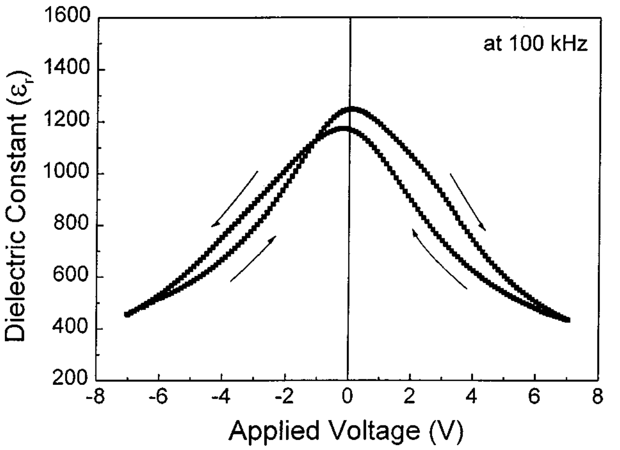

Fig. 8. Dielectric constant of the Y-BT film as a function of dc bias voltage.

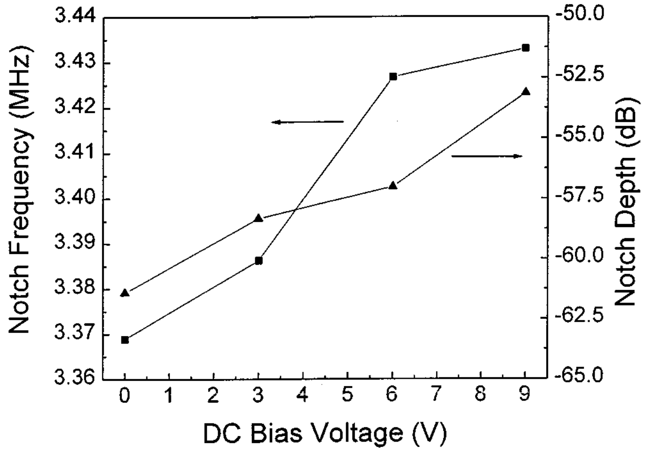

Fig. 9. Notch frequency and depth variation with dc bias voltage.

notch frequency should shift to higher values. The notch frequency and depth as a function of dc bias voltage are shown in Fig. 9. The notch depth decreased with increasing dc bias voltage when the notch resistance was kept constant.

The behavior of this structure as a tunable notch filter using a voltage-variable capacitance with various lumped-notch resistances and dc bias voltage will be optimized for use in integrated-circuit network applications at radio frequencies.

IV. CONCLUSIONS

Dielectric (Y-BT) and resistive (TaN) films for distributed RC notch filters were fabricated by pulsed laser deposition (PLD). The dielectric constant and dissipation factor (tanδ) of Y-BT films at 10 kHz were 1150 and 0.03, respectively. TaN films had a sheet resistance of 670 Ω at room temperature and a temperature coefficient of resistance (TCR) of -920 ppm/°C.

A notch frequency of 2.8 MHz and depth of -76.7 dB were measured at a notch resistance (R_N) of 34 Ω for a 316.2 μm × 316.2 μm distributed filter. Experimental optimum notch parameters of $\alpha = R/R_N = 19.7$ and $x_n = \omega/\omega_o = 33.0$ were obtained. Tunability of the notch frequency with dc bias voltage was also observed. With further optimization of the insertion loss, these characteristics of the thin film DRC notch filters should allow them to be used in integrated-circuit network applications at radio frequencies.

REFERENCES

[1] L. P. Huelsman, “The distributed-lumped-active network,” *IEEE Spectrum*, vol. 6, p. 51, Aug. 1969.

[2] W. M. Kaufman, “Theory of monolithic null device and some novel circuit applications,” *Proc. IRE*, vol. 48, p. 1540, 1960.

[3] W. M. Kaufman and S. J. Garrett, “Tapered distributed filters,” *IRE Trans. Circuit Theory*, vol. 9, p. 329, 1962.

[4] K. L. Su, “RC filters with staggered notch frequencies,” *Proc. IEEE*, vol. 54, p. 1199, Sept. 1966.

[5] S. Ahmad and R. Singh, “A composite dielectric thin film notch filter,” *Thin Solid Films*, vol. 67, p. L63, 1980.

[6] E. S. Kolesar, “Effects of thin film spin-on glass dielectric loss on the performance of the uniformly distributed RC notch network,” *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. 14, p. 413, June 1991.

[7] P. L. Swart and C. K. Campbell, “A voltage-controlled tunable distributed RC filter,” *Solid-State Circuits*, vol. SC-7, p. 306, 1972.

[8] P. H. K. Wong and L. Young, “A new voltage-tunable distributed RC notch filter suitable for SOS realization,” *Proc. IEEE*, vol. 62, p. 523, Apr. 1977.

[9] H. F. Benz and R. J. Mattauch, “A linear voltage-tunable distributed null device,” *IEEE J. Solid-State Circuits*, vol. SC-7, p. 499, Dec. 1972.

[10] S. Lucyszyn and I. D. Robertson, “MMIC tunable active notch filter,” *Electron. Lett.*, vol. 32, p. 980, 1996.

[11] P. S. A. Evans, B. J. Ramsey, P. M. Harrey, and D. J. Harrison, “Printed analogue filter structures,” *Electron. Lett.*, vol. 35, p. 306, 1999.

[12] W. Choi, Y. Tsur, C. A. Randall, and S. Trolier-McKinstry, “Effect of Y-doping on the dielectric properties of $BaTiO_3$ films deposited in reducing atmospheres using pulsed laser deposition,” in Proc. MRS, 1999, to be published.

[13] S. Sato, Y. Nakano, A. Sato, and T. Nonura, “Effect of Y-doping on resistance degradation of multilayer ceramic capacitors with Ni electrodes under the highly accelerated life test,” *Jpn. J. Appl. Phys.*, vol. 36, p. 6016, 1997.

[14] Y. Nakano, A. Sato, A. Hitomi, and T. Nonura, “Microstructure and related phenomena of multilayer ceramic capacitors with Ni-electrode,” *Ceramic Trans.*, vol. 32, p. 119, 1993.

[15] K. Radhakrishnan, N. Geok Ing, and R. Gopalakrishnan, “Reactive sputter deposition and characterization of tantalum nitride thin films,” *Mater. Sci. Eng.*, vol. B57, p. 224, 1999.

[16] C. Au, W. Anderson, D. Schmitz, J. Flassayer, and F. Collins, “Stability of tantalum nitride thin film resistors,” *J. Mater. Res.*, vol. 5, no. 6, p. 1224, 1990.

[17] B. Jaffe, W. R. Cook Jr., and H. Jaffe, *Piezoelectric Ceramics*. New York: Academic, 1971.

[18] J. A. Carson, C. K. Campbell, P. L. Swart, and F. J. Vallo, “Effects of dielectric losses on the performance of evaporated thin film distributed RC notch filters,” *IEEE J. Solid-State Circuits*, vol. SC-6, p. 120, June 1971.

Won-Youl Choi received the B.S. degree from Hanyang University, Seoul, Korea, and the M.S. and Ph.D. degrees in materials science and engineering from the Korean Advanced Institute of Science and Technology, Taejon.

He was a Postdoctoral Researcher with the Materials Research Laboratory, Pennsylvania State University, University Park. In 2000, he joined the Samsung Advanced Institute of Technology, Suwon, Korea, as a Special Researcher. His main research interests include ferroelectric thin films for dielectric applications, the characterization of the electrical and mechanical properties of thin films, and micromachining technology for microsensors and microactuators.

Susan Trolier-McKinstry (M’92) received the M.S. and Ph.D. degrees in ceramic science from Pennsylvania State University (PSU), University Park.

She is an Associate Professor of Ceramic Science and Engineering and Associate Director of the Materials Research Laboratory, PSU. Her main research interests include ferroelectric thin films for actuator and dielectric applications, the development of texture in bulk ceramic piezoelectrics, and spectroscopic ellipsometry. She has held visiting appointments at Hitachi Central Research Laboratory, the Army Research Laboratory, and the Ecole Polytechnique Federale de Lausanne.

Dr. Trolier-McKinstry received the Robert Coble Award of the American Ceramic Society, the Wilson Award for Outstanding Teaching in the College of Earth and Mineral Sciences, and an NSF CAREER grant. She is a member of the American Ceramic Society, the Materials Research Society, ASM, and ASEE. She is co-chair of the committee revising the IEEE Standard on Ferroelectricity. She is an Elected Member of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society Advisory Committee. She is past-President of Keramos and Treasurer for the Ceramics Education Council.