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Low temperature performance of some electronic devices and circuits for space applications

by:

Doaa Hassan Hanafy Mahmoud

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Supervised by

Prof. Dr. Eng. Fouad A. S. Soliman

Professor of Electronics & Computer Eng.
Head, Electronics Engineering Dept.,
Nuclear Materials Authority.

Prof. Dr. Thanaa A. Kamh

Professor of Electronics,
Physics Dept., Faculty of Women for
Arts, Science, and Education,
Ain Shams University.

Dr. Safaa M. R. El-Ghanam

Assistant Professor of Electronics,
Physics Dept., Faculty of Women for Arts,
Science, and Education,
Ain Shams University.

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Supervision Committee

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Doaa Hassan Hanafy Mahmoud

Submitted for Partial Fulfillment of Master Degree in Science

Approved by: ***Signature***

Prof. Dr. Eng. Fouad A. S. Soliman
Professor of Electronics & Computer Eng.
Head, Electronics Engineering Dept.,
Nuclear Materials Authority.

Prof. Dr. Thanaa A. Kamh
Professor of Electronics,
Physics Department, Faculty of Women,
Ain-Shams University.

Dr. Safaa M. R. El-Ghanam
Assistant Professor of Electronics,
Physics Department, Faculty of Women,
Ain Shams University.

بِسْمِ اللهِ الرَّحْمنِ الرَّحِيمِ

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ مِنْ أَمْرِ رَبِّي وَمَا أُوتِيتُمْ مِّنَ الْعِلْمِ إِلاَّ قَلِيلاً

[الإسراء : ٨٥]

Dedicated

To

My parents (Father and Mother),

My husband,

My brother,

My sisters,

My cognates,

My professors

and

My colleagues

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I am kneeling obsequiousness to ALLAH thanking HIM for showing me the right way. Without God help, my efforts would have gone astray. It was through the grace of God that I was able to acquire this great accomplishment. Thanks also for a person I love him very much, the Prophet Mohammed {God's praise and peace upon}.

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ABSTRACT

The present thesis is devoted in a trial to shed further light on two attractive electronic devices, namely; quartz crystals and ceramic resonators. Also, the study was extended to include most applications of both devices as an electronic filters and oscillators. In this concern, the electrical properties of different quartz crystals (operates at frequency values of ٢,٤٥٧ MHz, ٣,٥٧٩٥٤٥ MHz and ٤,٠٠ MHz) and ceramic resonators (covering the frequency range from ٤٠٠ kHz up to ٤,٠٠ MHz) and their applications as electronic filters and oscillators were investigated. Finally, the study was extended to include the operation of such devices at very low temperatures down to cryogenic levels simulating their applications at outer space.

The main static electrical parameters of the proposed devices (impedance (Z), equivalent parallel inductance (L_p), equivalent parallel capacitance (C_p), equivalent parallel resistance (R_p), phase angle (φ), dissipation factor (D), and quality factor (Q), were plotted as a function of frequency. Also, the elemental composition of the proposed ceramic resonator samples was determined applying the EDXRF technique, where ceramic samples were proved to be with major components of Lead (Pb), Zirconate (Zr), and Titanite (Ti).

The design and analysis of different filter - and oscillator - circuits based on both devices were investigated experimentally, and the obtained results were compared with those results obtained from simulation; applying Electronic Workbench programs, and theoretically; calculated applying computer programs using MATLAB language.

It is to be noted that, for both devices, the stability of their circuits either used as filters or oscillators was proved to be better than ٩٥ %, whenever circuit passive elements tolerated to extreme values, up to more than ±٢٠٪ of their initial circuit design values.

Considering low temperature levels applications, for quartz samples, their static characteristics were studied at the investigated temperature range (ITR) from ٢٩٣ K down to ٩٣ K, where, the obtained data were analyzed at the two main frequencies of the devices, i.e., resonance (F_r) - and anti-resonance (F_a) - frequencies. For ٣,٥٧٩٥٤٥ MHz quartz crystals, as an example, and at F_r, the dependences of C_p, φ, and D on temperature were shown to follow U- distribution curve shapes, where their initial values of ٣٠٨ pF, -٧٩,٧٨ and ٠,١٦ were shown to exhibit minimum values of ٥٣,٢ pF, - ٨٣,٤٥°, and ٠,١١, measured at temperature range of around ١٦٠-٢٠٠ K. For lower temperature levels, down to ٩٣ K, the previous three parameters exhibit values of ٤٥٦ pF, -٥٩,٧٣° and ٠,٢١, respectively.

On the other hand, the dependence of L_p, Z, R_p, and Q on temperature were shown to follow an opposite trend, i.e., nearly, obey, the Gaussian distribution shapes, where their initial values of

٠,٠٠٦٤ mH, ٠,١٤٣ kΩ, ٠,٨٨ kΩ, and ٦,١٦ show maximum values of ٠,٠٤١ mH, ٠,٨٣ kΩ, ٥,٤٧ kΩ, and ٨,٦١, respectively, occur at temperature range of around ١٦٠ - ٢٠٠ K. Also, and for lower temperature levels, down to ٩٣ K, their values were shown to be dropped down to ٠,٠٨٦ mH, ٠,١٨ kΩ, ٠,٩٦ kΩ and ٤,٧٤, respectively.

For the same quartz crystal samples, and at F_a, it was proved that also, the dependence of C_p, φ, and D on low temperatures obey the Gaussian distribution curve shape, where their initial values of ١,٩٥ pF, -٦٥,١٢°, and ٠,٨٥ were shown to increase, reaching maximum values of ٣,٥ pF, -٦٠,١٥°, and ٢,٠٢ occur at temperature range of around ١٦٠ - ٢٠٠ K. While for lower temperatures levels, down to ٩٣ K, their values were shown to decrease down to ٢,٢٤ pF, -٦٣,١°, and ٠,٧٩, respectively. Finally, considering L_p, Z, R_p, and Q, their dependence on temperature were shown to obey the U-distribution shapes, where their initial values of ١,٠١ mH, ٢٠,٦ kΩ, ٤٨,٨ kΩ , and ١,١٦ show minimum values of ٠,٥٥ mH, ٨,٤٤ kΩ, ١٧,١ kΩ, and ٠,٥, located at around ١٦٠- ٢٠٠ K. Again, for lowering the temperature down to ٩٣ K, their values were shown to increase up to ٠,٨٨ mH, ١٧,٧ kΩ , ٣٩,٢ kΩ, and ١,٧٣, respectively.

Considering the square wave oscillators - based on quartz crystals namely; Pierce in CMOS (٧٤HCO٤), CMOS Two-Inverters – (٧٤HC٠٤), and TTL Two-Inverters-(٧٤S٠٤), their oscillation frequencies were shown to be almost temperature independent within the investigated temperature range, where the maximum observed shifts on their values from the predetermined oscillation frequencies were shown to be around ٠,٤ %, ٠,٠٧٦ %, and ٠,١٩٦ %, respectively.

Concerning the operation of the ceramic resonators, for CRB٤٥٥ kHz ceramic resonator, as an example, it was proved that, at F_r, the values of C_p, R_p, and φ were shown to decrease with lowering the temperature down to ٩٣ K with a ratio of around ٨١,٦ %, ٣٦,٢ %, and ١٥,٧ %, respectively. On the other hand, the rest parameters L_p, and Z were shown to increase several times of their initials (about five, and three times, respectively) as a function of lowering temperature. Besides, at F_a, the dependence of C_p on temperature, within the ITR, was shown to follow nearly U-distribution shape, where its initial value was ٤,٥٠ pF shows a minimum value of ٢,١٨ pF, measured within temperature range of around ١٨٠ K-٢٠٠ K. While, lowering the temperature down to ٩٣ K, its value was shown to increase up to ٤,٨ pF.

On the other hand, L_p shows an opposite trend, i.e., obeys Gaussian distribution shape, where its initial value of ٢٦,٦ mH shown to increase, reaching maximum value of ٥٧,٦ mH, measured at the same temperature range (around ١٨٠ K – ٢٠٠ K).

For lower temperatures, down to ٩٣ K, its value was shown to decrease again down to ٢٥,٣ mH. On the other hand, Z, and R_p were shown to decrease pronouncedly with decreasing temperature with a ratio of around ٣٩ %, and ٧٣ %, respectively.

The resonance-, and anti-resonance-frequencies, as well as, the center frequency were shown to be shifted toward lower frequency values, as a function of lowering temperature in the range from room level down to around ١٥٠ K -١٦٠ K. For lower temperature levels, down to ٩٣ K, their values were shown to increase exponentially, again, the matter which is attributed to the recorded changes on the equivalent circuit elements of the devices.

Ceramic resonators operation, in the temperature range from room level down to ٩٣ K, was considered. In this concern, filter circuits (band reject filter, band- pass filter, and trap filter), and oscillator circuits (square wave oscillator and sine wave oscillator) were investigated.

For the band reject filter circuit, the main change on its response curve was shown as an increase in the voltage value at stop-band, where its initial value of ١,٦٠ Volts was shown to increase exponentially up to ٤,٤٠ Volts within the predetermined temperature range. While, for the band pass filter circuits, decreasing the temperature down to around ١٣٠ K leads both the center frequency and selectivity to decrease with ratios of around ١,٠ % and ١٢,٠ %. On the other hand, and for temperature levels below ١٣٠ K, both parameters were shown to increase with ratios of around ٠,٣ % and ٣,٠ %, respectively. In contrast, the filter pass band width was shown to increase with a ratio of around ٣٣,٠ %, for the first temperature range. While for the second temperature range, its value was shown to decrease with ratio of around ٨,٣ %.

On the other hand, the insertion loss was shown to decrease with a ratio of around ١٣,٧٥٪. In contrast, V_{pp} max. was shown to increase with a ratio of around ١٣,٠%.

Also, for the trap filter circuit, the main changes occur on its frequency response was shown to be an increase in the voltage value at stop-band, where an initial value of ١,٠ Volt, measured at room temperature was shown to increase exponentially up to ٤,٥٠ Volts, measured at ٩٣ K.

Considering the oscillator circuits based on ceramic resonators, and for the square wave oscillators the recorded main changes on their electrical parameters were shown to be an increase exponentially in both the rise- and fall- times parameters, with ratios of around ١٥,٠ % and ٢٤,٧ %, respectively. On the other hand, for the sine wave oscillators, decreasing temperature leads the values of the parameters V_{pp} and RMS to decrease exponentially with a ratio of around ٥٠,٠٪, and ٤٦,٠٪, respectively. On the other hand, all of the frequency, period and mean parameters are being appears constant with decreasing temperature.

LIST OF SYMBOLS & ABBREVIATIONS

B.P. : Band-Pass

B.R. : Band-Reject

B.W : Pass Band Width (Hz)

C_p : Equivalent parallel capacitance (F)

C. : Shunt capacitance (F)

CMOS : Complementary Metal–Oxide–Semiconductor

CPC : Coated Piezoelectric Crystal

DRIE : Deep Reactive Ion Etching

D-Factor : Dissipation Factor

EDXRF: Energy Dispersive X- ray Florescence System

F_r : Resonance frequency (Hz)

F_a : Antiresonance frequency (Hz)

F_o : Center frequency (Hz)

Hz : Frequency (Hz)

H.P. : High-Pass

IC : Integrated Circuit

K : Temperature (Kelvin)

K_{eff} : Effective electro-mechanical coupling coefficient

L_p : Equivalent parallel inductance (H)

L.P. : Low-Pass

MATLAB : Mathematics Laboratory

NPS : Nitrated Polystyrene

PZT : Lead Zirconate Titanate

ppm : part per million

PQC : Piezoelectric Quartz Crystal

Q- Factor : Quality Factor

QCM : Quartz Crystal Microbalance

R_p : Equivalent parallel resistance (Ω)

RH : Relative Humidity

SAW : Surface Acoustic Wave

TTL : Transistor-Transistor Logic

TFC : Temperature-Frequency Characteristics

XRF : X-Ray Florescence Analysis

XRD : X-Ray Diffraction Analysis

Z : Impedence (Ω)

Φ : Phase Angle (Degree)

Period : Reciprocal of frequency (sec).

V_{pp} : Absolute difference between the maximum and minimum amplitude in the entire waveform or gated region (Volt).

High Voltage : The maximum output voltage without ripples(Volt).

Low Voltage : The minimum output voltage without ripples (Volt).

Pos. Duty Cycle : Timing measurement of the first cycle in the waveform or gated region. The ratio of the positive pulse width to the signal period expressed as a percentage.

$$PostiveDutyCycle = \frac{PostiveWidth}{Period} x100$$

Neg. Duty Cycle : Timing measurement of the first cycle in the waveform or gated region. The ratio of the negative pulse width to the signal period expressed as a percentage.

$$NegativeDutyCycle = \frac{NegativeWidth}{Period} x100$$

Rise Time, t_r : It is the time taken by the output voltage (or current) to rise from ١٠٪ to ٩٠٪ of its maximum value (sec).

Fall Time, t_f : It is the time interval during which the output voltage (or current) falls from ٩٠٪ of its maximum value to ١٠٪ (sec).

RMS : The Root Mean Square voltage over the entire waveform or gated region (Volt).

Mean : The arithmetic mean over the entire waveform or gated region (Volt).

Pos Over Shoot : Voltage measurement over the entire waveform or gated region expressed as a percentage.

$$PostiveOvershoot = \frac{Max - High}{Amplitude} x100$$