A Review of the Recent Development of Temperature Stable Cuts of Quartz for SAW Applications

C.S. Lam, Chris Y.J. Wang and S.M. Wang
TXC Corporation, Ping Cheng City, Taoyuan County, Taiwan

Abstract

Quartz continues to be used widely in frequency control applications due to its temperature stability and low cost. In specific, ST-cut quartz provides the best performance in narrow band SAW filter, SAW resonator, SAW oscillator, clock and data recovery unit, frequency translator, etc. Since the discovery of the even more stable LSAW-based quartz LST-cut in 1985, a few more new quartz cuts based on LSAW, HVPSAW, etc. were introduced and some of them were actually being used in telecom SAW products. This paper reviews the development of these temperature stable quartz cuts for SAW applications in the past and discusses possible future development.

I. Introduction

Quartz continues to be used widely in frequency control applications due to its temperature stability and low cost. From the early application of ST-cut of quartz for SAW products, many more new cuts were introduced. We first review the linkage of BAW and SAW through the discussion of singly-rotated AT-cut quartz plate, doubly-rotated SC-cut quartz plate, SAW on ST-cut quartz wafer, and STW on singly-rotated quartz wafer. We then review the development of the LST-cut, K-cut and in-plane rotated 33° Y-cut of quartz. The recent development of HVPSAW on quartz is discussed in the end.

II. BAW and SAW

For many years, researchers of acoustic wave devices for electronics applications seem to be separated into two camps- the BAW group (or sometimes called the "crystal" group) and the SAW group, and they don't seem to "mingle." BAW researchers are most familiar with the AT- and SC-cut thickness-shear quartz resonators. AT-cut is a singly-rotated Y-cut quartz plate (a Y-cut plate has its normal axis parallel to Y-axis) with $\theta \cong 35.25°$ (Fig. 1). SC-cut is a doubly-rotated Y-cut with $\theta \cong 33.93°$ and $\Phi \cong 21.93°$. In a way, one can use the "BAW Angles" (Φ, θ, ψ) to describe exactly a BAW plate. ψ is in general meaningless to a BAW plate as its vibration is "bulk" in nature (frequency α 1/thickness) with wave traveling across the thickness and the particle motion is in the X-axis direction. The current authors noted some in the industry began to use the term BAWR to mean FBAR (film bulk acoustic resonator). The BAW technology in this paper retains its conventional meaning.

SAW researchers instead are most familiar with using the Euler Angles (λ, μ, θ) to describe specific SAW cut and propagation direction. The most popular quartz cut is the ST-cut (ST = Temperature Stable) which has Euler Angles (0º, 132.75º, 0º). It is sometimes called the "X-propagation rotated Y-cut direction." The Euler Angles (λ, μ, θ) can be related to the BAW Angles (Φ, θ, ψ) by

$\lambda = \Phi$
$\mu = \theta + 90°$
$\theta = -\Psi$

And so ST-cut quartz for SAW is basically an "AT-cut BAW plate" with θ = 42.75º and the SAW propagates in the X-axis. The BAW Angles are (0º, 42.75º, 0º). Any off X-axis SAW propagation can then be described by a non-zero Ψ (e.g. NSPUDT cut of quartz has $\Psi \cong \pm 25°$). Understanding the BAW Angles and Euler Angles allows one intuitively to link the BAW and SAW technologies.

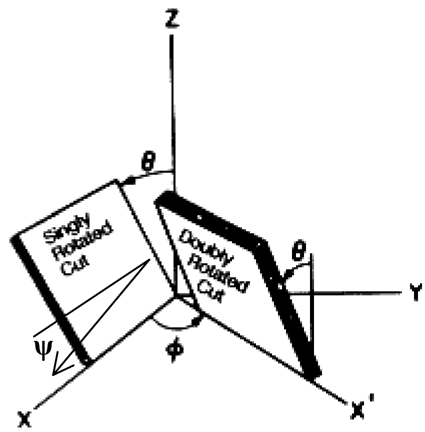

Fig. 1 Singly- and Doubly-Rotated Y-Cut Quartz Plates

Though limited to low frequency applications, AT- and SC-cuts exhibit cubic frequency-change vs temperature ($\Delta f/f$ vs T). Depend on the temperature range of operation, BAW resonators can offer $\Delta f/f$ stability anywhere between 10 to 100 ppm. ST-cut exhibits quadratic $\Delta f/f$ vs T with a 2nd order temperature coefficient of ~–0.034(T-To)^2 where To is the turnover temperature (TOT). Assuming the temperature range of operation is –40 to 85ºC and the TOT is well centered at 22.5ºC, the $\Delta f/f$ is at least ~130 ppm. Changing the angle θ in Fig. 1 (away from 42.75º) can shift the TOT but it doesn't improve the temperature coefficient. In the mid-70's, SAW researchers noted Surface Skimming Bulk Wave (SSBW) with

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horizontal shearing particle motion can be efficiently excited with SAW transducers aligned with $\theta \cong 36^\circ$ and $\psi = \pm 90^\circ$ equivalent to Euler Angles (0º, 126º, ±90º). It is also referred as Z'-propagation rotated Y-cut direction. SSBW became Surface Transverse Wave (STW) when well trapped by the periodic structure of the transducers. This wave travels at ~1.6 times of the SAW velocity in the regular ST-cut such that it is convienent for high frequency operation. Unfortunately, the quadratic Δf/f vs T has higher 2^{nd} order temperature coefficient of ~–0.052(T-To)^2. Hence for many years, SAW technology though can be used in high frequency products, it doesn't offer as stable frequency-temperature performance as the BAW technology.

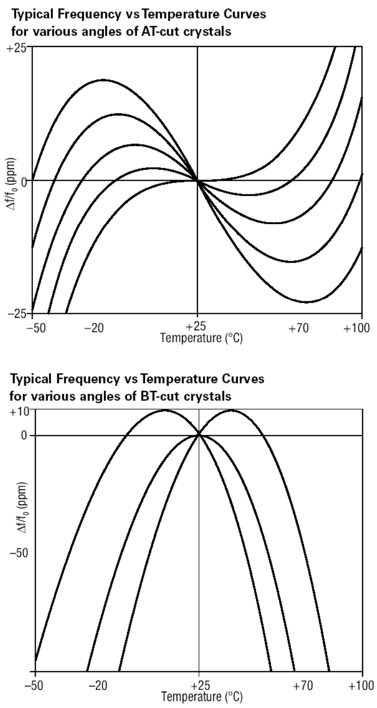

Fig. 2 Δf/f vs T of AT- and BT-Cut Quartz

BAW researchers are also familiar with BT-cut of quartz with BAW Angles (0º, -49º, 0º). Since the thickness-shear velocity is lower than that of the AT-cut's, BT-cut is sometimes used when one prefers to process thicker plate of the same frequency. BT-cut doesn't has as good frequency-temperature performance since its Δf/f vs T is quadratic (Fig. 2). Fig. 3(a) depicts the BT-cut for BAW operation and the 36º for STW operation (noted that the angle difference is ~90º). The thickness-shear BAW and STW propagate in the Z'-axis direction. The particle motion is in the X-axis direction for both cases. One recalls both operations exhibit quadratic Δf/f vs T. Fig. 3(b) depicts the AT-cut and the arrow indicates the thickness-shear BAW propagation direction. The particle motion is again in the X-axis direction. Based on what we observed in Fig. 3(a), one may ask "Is there a SAW or STW cut at ~90º away from the AT-cut which exhibits cubic Δf/f vs T? If not, why not?" [1] In the past many years, SAW researchers discovered other SAW quartz cuts which offered good frequency-temperature performance[2~3].

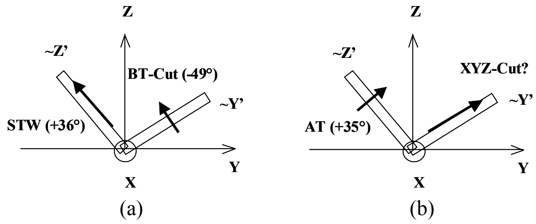

Fig. 3 AT- and BT-cut of Quartz and STW Operation[1]

However, many of these were doubly-rotated Y-cut quartz with Euler Angles ($\lambda \neq 0^\circ$, $\mu \neq 0^\circ$, θ). These cuts are difficult to be processed from quartz stones as two angles needed to be held. They are also expensive (similar to the SC-cut in BAW applications) and do not see commercial acceptance.

III. Past Development of LST-Cut Quartz

The SAW and STW (well trapped SSBW) on quartz described in the previous section were true generalized surface wave and slow-shear surface wave, respectively. The generalized SAW has a surface wave velocity lower than that of bulk slow shear wave. The STW has a surface wave velocity close to that of the bulk slow shear wave.

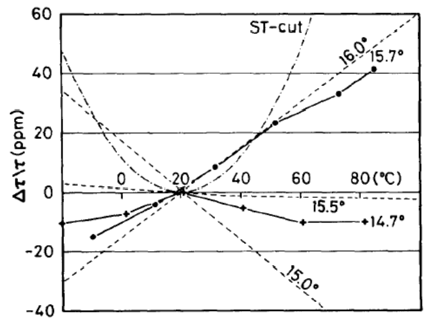

Fig. 4 Δτ/τ vs T for ST- and LST-Cut Quartz[5]

In 1985, Shimizu et al.[5,6] discovered a new cut of quartz with exceptional frequency-temperature performance (Fig. 4). The cut has Euler Angles (0º, ~15º, 0º) with X-axis propagation.

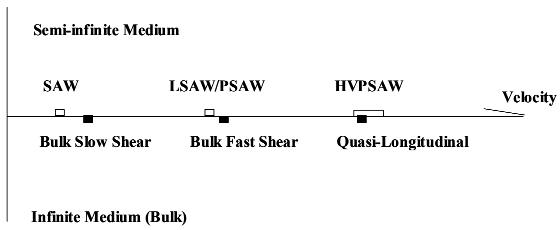

Fig. 5 Bulk and Surface Waves

The wave type is leaky surface acoustic wave (LSAW) that leaks energy into the bulk as it traverses. And so this cut of quartz was named LST-cut (leaky stable temperature cut). The leakage for this cut was found to be small (~0.0026 dB/λ). LSAW in general has higher velocity than that of the bulk slow shear wave (Fig. 5) and its particle motion is shear predominant. The velocity of the LST-cut is indeed ~25% higher than that of the ST-cut. Table 1 lists the comparison of the key parameters of these two cuts. It is noted in special case where leakage is zero and velocity is above the bulk slow shear wave, the term pseudo surface acoustic wave (PSAW) is sometimes used to describe such wave type which is true surface wave.

	ST-Cut	LST-Cut
Rotated Y-Cut (º)	42.75	~ -75
Velocity (m/s)	3158	3960
Coupling Constant (k^2)	0.0016	0.0011
Attenuation (dB/λ)	0	0.0026

Table 1 Comparison of ST- and LST-Cut Quartz

LST-cut quartz attracted much attention as it offered good frequency-temperature performance. The study of it continued for a few years including using gold film as the metallization.[7,8] LST-cut also saw some real applications[9,10] in the late 80's and early 90's. However, researchers were not able to resolve some critical issues- high sensitivity to metallization thickness, cut angle tolerance, increase of leakage as temperature rises (Fig. 6), etc. [11~13]

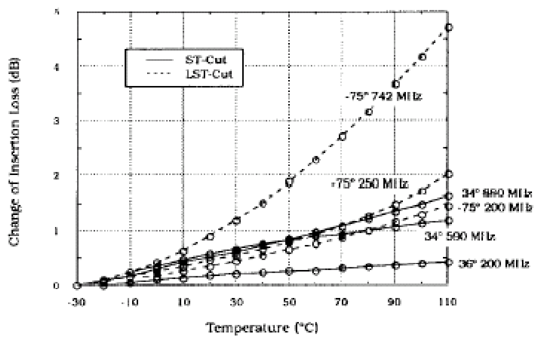

Fig. 6 Leakage Increase vs T for LST-Cut Quartz[11]

Study of this cut subsided almost for the rest of the 90's. Interesting enough, the first reporting of leakage-temperature[11] relationship for LSAW in the early study of LST-cut quartz proved to be partially responsible for the industry's abandoning of the conventional 36º YX $LiTaO_3$ LSAW cut for RF SAW filters in mobile handsets in the late 90's and the beginning of using 42º YX $LiTaO_3$ which was found to offer optimal performance (steeper skirt and lower insertion loss) over temperature.[14]

IV. Recent Development of LST-Cut Quartz

Since the late 90's and early 00's, renewed interest in LST-cut quartz began to appear. This was partly due to the increase in market demand of higher frequency oscillators with BAW-type frequency-temperature performance. In 1999, Yong et al. began to use finite element analysis (FEA) to study LST-cut quartz (Fig. 7).[15] Yong proposed an elegant parameter "mean attenuatiion factor" which was defined as the ratio of the root mean square of the displacement in the top half of the substrate to its bottom half. It was a relative measure of the "leakiness" of the LSAW modes. A LSAW mode with its energy well confined near the top surface would have a high mean attenuation factor. The BAW modes would have a mean attenuation factor close to one, while the bottom LSAW mode would have a mean attenuation factor much less than one. In 2003[16], Yoon also used commerical FEA tool to study the effect of the finite thickness of LST-cut quartz substrates on the dispersion of LSAW.

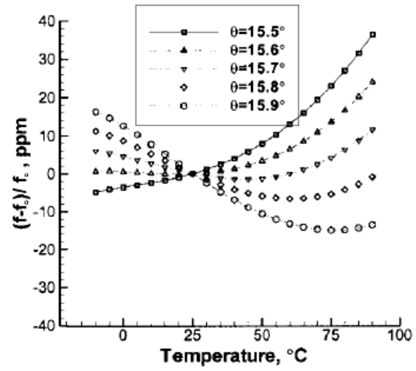

Fig. 7 FEA Results of Δf/f vs T for LST-Cut Quartz[15]

In 2002, Watanabe, one of the discoverers of LST-cut quartz in 1985, maintained his passion toward this cut and developed innovative multi-wire-sawing method to slice LST-cut SAW wafers from lumbered quartz Z-bar. It was believed, by bringing the tolerance of LST-cut angle at 16.2º to within ±0.2º, the frequency variation and insertion loss change would be held to minimum.[17]

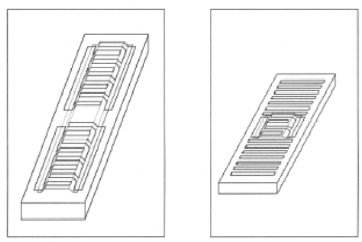

Fig. 8 Raised Transducer Structure on LST-Cut of Quartz[18]

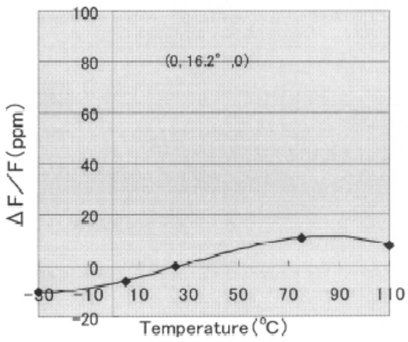

Fig. 9 Δf/f vs T for Raised Transducer Structure on LST-Cut Quartz[18]

In the same year, Watanabe demonstrated a raised-transducer structure (Fig. 8) on LST-cut quartz so to remove the electrode film thickness dependency. The change of frequency for a 200 MHz device was within ±20 ppm in a temperature range of –30 to 110ºC (Fig. 9).[18] The insertion loss change was under 0.5 dB. The best result recently obtained by the current authors for a 622 MHz 1-port SAW resonator using surface electrodes is as shown in Fig. 10 (-73º cut, mark period ratio = 0.4, and H/λ = 1.0). A better than ±50 ppm was obtained for temperature range –30 to 70°C. The study continues.

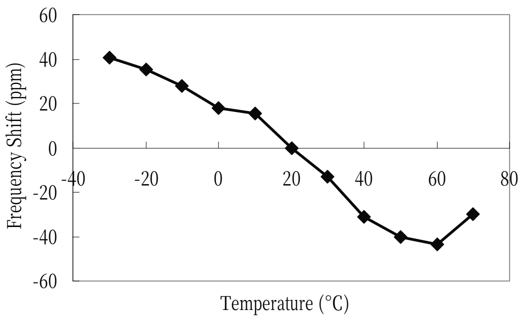

Fig. 10 Δf/f vs T for a 622 MHz SAW Resonator on LST-Cut Quartz

V. K-Cut Quartz

During the "siesta" of the study of LST-cut quartz in the mid 90's, a new static and dynamic temperature stable cut of quartz was introduced. In 1996[19~21], Takagi et al. introduced a cut of quartz with Euler Angles (0º, 96.5º, 33.8º) which offered better 2nd order temperature coefficient (~–0.028(T-To)^2) than ST-cut, TOT (θ_{max}) near to room temperature and a modest k^2 (Table 2). The cut was still a singly-rotated Y-cut (such that easy to process) except with off X-axis propagation which resulted in a small power flow angle (PFA). The measured phase velocity based on a 152 MHz SAW resonator using a cut with Euler Angles (0º, 96.5º, 32.43º) was 3308.2 m/s. Our calculation yielded the following results-

Phase velocity (shorted) = 3305.7981 m/s
Phase velocity (open) = 3307.7022 m/s
Electromechanical coupling factor (k^2) = 0.001151
PFA = 3.63º

The k^2 and PFA are very close to those reported in Table 2. The average phase velocity is ~3306 m/s which is ~5% higher than that of ST-cut. K-cut was first deployed in 100~150 MHz fixed frequency SAW oscillators[22,23] to compete with BAW-based oscillators, which at such frequencies, needed to use 3rd overtone BAW AT-cut crystal resonators.

$\phi = 0$

Name of cut	ST*	J	K	L	M
θ (°)	123.0	11.25	96.51	10.46	0.00
ψ (°)	0.0	21.59	33.79	69.11	55.15
$k^2(\times 10^{-2}\%)$	17	7	11	3	2
PFA (°)	0.0	0.81	2.53	4.64	−5.3
θ_{max} (°C)	20.0	68.8	22.2	−25.5	−24.4
$\beta(10^{-8}/°C^2)$	−3.4	−33.5	−2.78	−4.76	−4.8

ST*: measured value.

Table 2 Comparison of ST- and K-Cut Quartz[20]

Though K-cut quartz offers better frequency-temperature performance than that of the ST-cut quartz, it still can't compete with the cubic Δf/f vs T of the conventional BAW AT-cut crystal resonator. The integrated phase jitter of SAW-based oscillator seems to be better than that of the 3rd overtone crystal oscillator. Arguments continue till today on which technology actually offers the better performance.[24,25] The current authors believe each finds its own acceptance by customers for different applications.

VI. In-Plane Rotated 33° Y-Cut Quartz

In 2002[26,27], Kanna et al. introduced an "in-plane rotated 33° Y-cut quartz" which had an even smaller 2nd order temperature coefficient of ~–0.014(T-To)^2 (Fig. 11). Theoretically, Δf/f for this cut can be as low as ±50 ppm for a temperature range of –40 to 80°C. The Euler Angles for this cut were (0°, 123°, 39~44°) and so it's still a singly-rotated Y-cut. Kanna demonstrated a 644 MHz SAW resonator using this quartz cut with impedance ~11Ω and Q>10,000. The SAW parameters for this cut were not revealed when it was first introduced. Our calculation for Euler Angles (0°, 123°, 41.5°) yielded the following results-

Phase velocity (shorted) = 3251.5286 m/s
Phase velocity (open) = 3253.4841 m/s
Electromechanical coupling factor (k^2) = 0.001202
PFA = 1.35º

The average phase velocity is ~3252 m/s which is ~3% higher than that of ST-cut. k^2 is close to that of ST-cut and it has a small PFA. It is believed that such cut is now being deployed in high frequency SAW oscillator applications in Japan.

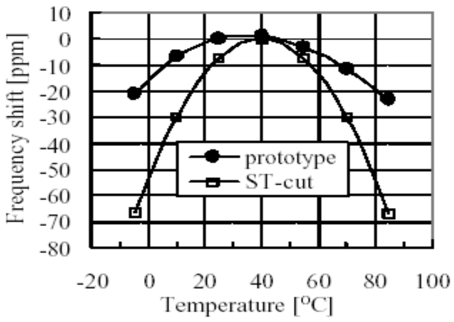

Fig. 11 Δf/f vs T for ST- and In-Plane Rotated 33° Y-Cut of Quartz[26]

VII. Quartz Cuts Employing High Velocity Pseudo Surface Acoustic Wave

In 1988, Zaslavsky et al.[28] studied experimentally the possibility of using "longitudinal near-surface volume acoustic waves" in SAW devices. The waves were basically SSBWs with dominating longitudinal particle motions. In ST-cut quartz, it appears at around 1.8 times the generalized surface wave frequency and has always been considered as spurious.

Material and orientation (Euler angles [°]) v_{BULK} [Km/s]	v_p short/ open (v_{SAW}^{FREE}) [Km/s]	α short/ open [dB/λ]	Fields @ $z=0$ u_x, u_y, u_z, short/open (magnitude [Km]) Symmetry type	PFA[°] short/ open $2\lvert\Delta v_p\rvert/v_p$ [%]
$LiTaO_3$	6.2442	0.56	1 0.19 0.25	1.3
[90° 90° 31°]	6.3179	8.0e−3	1 0.09 0.13	3.5
[3.336 3.365 6.316]	(3.1420)		TYPE 1	2.3
36°YX-$LiTaO_3$	6.9049	0.80	1 0.11 0.60	−14.8
[0° −54° 0°]	6.9779	0.12	1 0.13 0.58	−12.0
[3.351 4.227 5.589]	(3.1252)		TYPE 1	2.09
quartz AT-X	5.7447	1.0e−2	1 0.12 0.077	−0.2
[0° −54.7° 0°]	5.7454	2.5e−3	1 0.12 0.080	−0.1
[3.298 5.100 5.744]	(3.1510)		TYPE 1	0.023
quartz ST-X	5.7446	6.0e−3	1 0.066 0.081	−0.5
[0° 132.75° 0°]	5.7449	1.2e−3	1 0.056 0.084	−0.7
[3.298 5.100 5.744]	(3.1576)		TYPE 1	0.011
quartz ST-25°	6.5262	1.8e−5	1 0.35 0.090	14.1
[0° 132.75° 25°]	–	–	–	–
[3.365 4.032 6.604]	(3.2475)		TYPE 1	–
GaAs	5.3987	1.9e−2	1 0.04 0.234	2.8
[45° −90° 25°]	5.3986	1.6e−3	1 0.04 0.233	2.9
[2.654 2.990 5.376]	(2.5339)		TYPE 1	0.004

Table 3 HVPSAW for Different Piezoelectric Substrates[30]

In 1979, Jhunjhunwala suggested that, since LSAW existed between the slow shear and fast shear waves, "secondary LSAW" could exist between the fast shear and quasi-longitudinal waves.[29] The velocity would be even higher than that of the regular LSAW but the wave could be of little usage because of suspected high leakage. In the mid 90's, SAW researchers began to study high velocity pseudo surface acoustic wave (HVPSAW) in some piezoelectric substrates, which seemed to offer low leakage loss, strong electromechanical coupling, and comparable temperature coefficient. Cunha et al. summarized his study (Table 3) in 1998.[30] One quartz cut example with Euler Angles (0°, -54.7°, 0°) that supported HVPSAW has-

Phase velocity (shorted) = 5744.7 m/s
Phase velocity (open) = 5745.4 m/s
Electromechanical coupling factor (k^2) = 0.00023

No temperature coefficients for this cut were reported. In 2000, Yong et al.[32] used FEA tool to study HVPSAW for quartz cuts with Euler Angles (0°, 125~140°, 0°). Yong projected the electrode height played a strong role in the frequency-temperature behavior and wave attenuation of the HVPSAW mode. An optimal electrode height and cut angle could be chosen to produce low-loss temperature stable HVPSAW resonator. The current authors believe the full potential of HVPSAW is yet to be exploited.

VIII. Discussion

Quartz continues to be the material of choice for stable temperature SAW applications. From the early investigations of generalized surface acoustic wave (Rayleigh Wave with also off-sagittal plane particle motion), STW, and LSAW to the recent development of HVPSAW, SAW researchers continue to gain new insights in what this material can offer. As recent as in 2000, Abbott et al.[33] discovered a quartz cut with Euler Angles (0°, 43°, 23.7°) which offered minimal diffraction, 15% higher electromechanical coupling than that of ST-cut quartz, near zero PFA, low frequency-temperature coefficient, and room temperature TOT. In the earlier days of SAW filter development, electrode finger reflection was to be supressed to reduce passband ripples. Finger reflection today instead is the corner stone allowing us to realise low-loss SAW filters. As in other sciences, SAW researchers sometimes need to slow down and look back what we missed in the past. What was "bad" in the past may now be important. With persistent study of this material, we shall see more surprises in the future.

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