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Impact of interface damping in high-frequency surface-wave resonances on nanostrip-attached substrates

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1.Introduction

Generated on periodic nanostrip-attached substrates, surface acoustic wave (SAW) and its' propagation behaviors have been intensively studied including band gaps, resonance frequency, attenuation, and so on.[1, 2)] Since these behaviors have the significant impact on the performance of SAW devices like sensors, oscillators and filters etc., it is very important to develop a precise theoretical model to clarify the parameters for structure designing.

In our previous work, we have revealed that the interface stiffness between strips and substrate has a significant influence on resonance frequency of high-frequency SAW.[3)] However, anelastic behavior at the interface, which is caused by interface dislocations, incohesive interface bonds, friction due to local dis-bonding, and so on, will cause significant energy loss and influence the surface-wave propagation behaviors. This effect has not been studied so far.

In this paper, we study the impact of interface damping between nanostrips and substrate in high-frequency (up to ~12 GHz) surface-wave resonances. Based on the previous model with interface stiffness, the interface damping is introduced to the new model. The numerical simulation results show that interface damping insignificantly affects the resonance frequency however, interestingly, attenuation of SAW will decrease significantly in high frequency region as interface damping increases. Furthermore, using the picosecond ultrasound spectroscopy, we confirm the validity of our theory; the experimental results show the similar trends both for resonant frequency and attenuation of SAW, which indicates the importance of considering the interface damping.

This study shows that the interface damping has an obvious impact on attenuation of high-frequency SAWs, which should be considered in the design of SAW devices.

2. Theory

We propose a two-dimensional model with interface stiffness and interface damping as illustrated in **Fig. 1**. x_1 defines the in-plane direction and x_3 defines the out-of-plane direction. We interpret the interface damping as the ratio of imaginary to real parts of the interface stiffness[4)]:

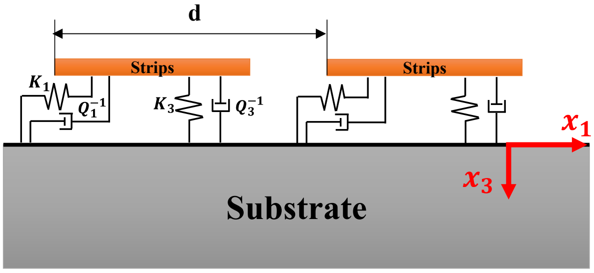

Fig. 1 Two-dimensional model with interface stiffness and interface damping

$$\widetilde{K}_j = K_j\left(1 + iQ_j^{-1}\right) \qquad j = 1{,}3.$$

Here, K_j is the interface stiffness and Q_j^{-1} represents the interface damping. Based on our previous study, we can get the matrix M formed by the system equations, which is a function of wavenumber k_1, frequency ω, and parameters of the structure. To obtain the meaningful solutions for nonzero coefficients, the determinant of the matrix M should be zero. This equation is solved by giving a real part of the surface-wavenumber $\mathrm{Re}\,(k_1)$, seeking the frequency ω and the imaginary part of the surface-wavenumber $\mathrm{Im}(k_1)$. The imaginary part $\mathrm{Im}(k_1)$ corresponds to the attenuation of leaky surface waves.[3)]

3. Experiment

Nanostrip structures are fabricated on (001) Si substrate by electron-beam lithography. A thin Titanium layer (1nm) is first deposited on the substrate to improve the bond strength between nanostrips and substrate. Then, permalloy ($Fe_{20}Ni_{80}$, ρ=8693g/cm^3) layer is deposited, whose thickness is about 20 nm. Also, to prevent the oxidation, a thin silica layer (2 nm) is deposited on the permalloy layer. After lithographic procedures, five groups of

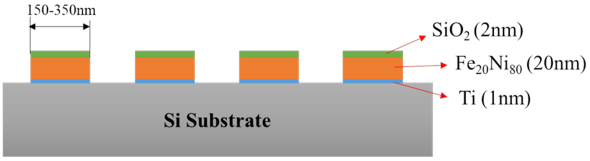

Fig. 2 Schematic of nanostrip-attached substrate structure used in experiment

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nanostrip structures with different widths between 150 nm and 350 nm are fabricated. The width of gaps is equal to the width of nanostrip; the period of nanostrip structures is from 300 nm to 700 nm, as shown in **Fig. 2**.

The SAW is generated and detected by the picosecond ultrasound spectroscopy. Details of the experiment can be found in our previous work.[3] The resonant frequency and attenuation of SAWs are determined by fitting the damping sinusoidal function to the experimental data.

4. Results and Discussions

The numerical simulation results and experiment results are shown in **Fig. 3**. The solid squares represent the experiment results. The black dashed line denotes the Rayleigh-wave resonance frequency, and the red dashed line is the numerical simulation result without interface damping. The colored solid lines are the numerical simulation results of the proposed model with interface stiffness and different interface damping.

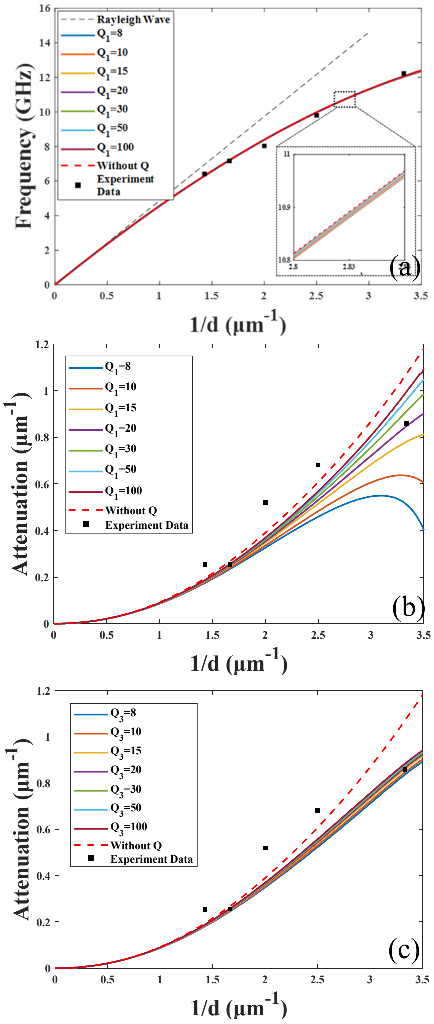

Fig. 3 Relationship between surface-wave (a) resonance frequency, (b) attenuation and reciprocal period, respectively, with different in-plane interface damping Q_1 when the out-of-plane interface damping Q_3 is 10. (c) Relationship between surface-wave attenuation and reciprocal period with different out-of-plane interface damping Q_3 when the in-plane interface damping Q_1 is 20.

In numerical simulation, for the first step, we can find the interface stiffness value ($K_1 = 2.64 \times 10^{18} J/m^4$ and $K_3 = 7.04 \times 10^{18} J/m^4$) by the resonance frequency curve fitting based on the previous model. Then, considering the interface damping should be different in different directions,[5] we assume a certain Q_3^{-1} value and introduce the different Q_1^{-1}, which can show the influence of in-plane interface damping. Also, the influence of out-of-plane damping Q_3^{-1} can be obtained in the same way.

From Fig. 3(a), it is shown that the surface-wave resonance frequency with different interface damping remains almost the same as the previous model. This is correct in physics because the damping should not influence the resonance frequency significantly. However, as shown in Figs. 3(b) and 3(c), the interface damping will make the attenuation decrease significantly in high frequency region, and it agrees with the experiment result when $Q_1 = 20$ and $Q_3 = 15$. It is also worth noting that the in-plane interface damping Q_1 has a larger impact on the attenuation compared with the out-of-plane interface damping Q_3.

This is very interesting because, if a new damping mechanism is introduced, the energy in the system would be more largely dissipated, and the attenuation would have increased. However, in this study, it seems that the interface damping acts as an obstacle of bulk wave radiation and can make the attenuation of SAW decrease. This mechanism has never been indicated so far.

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