Effect of Fe content on the interfacial reliability of SnAgCu/Fe-Ni solder joint

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Abstract

Fe-Ni films with compositions of Fe-75Ni, Fe-50Ni, and Fe-30Ni were used as under bump metallization (UBM) to evaluate the interfacial reliability of SnAgCu/Fe-Ni solder joints through ball shear test, high temperature storage, as well as temperature cycling. The shear strength for Fe-75Ni, Fe-50Ni, and Fe-30Ni solder joints after reflow were 42.57, 53.94, 53.98 MPa respectively, which are all satisfied with the requirement of industrialization (＞34.3 MPa). High temperature storage was conducted at 150°C and 200°C respectively. It was found that higher Fe content in Fe-Ni layer had the ability to inhibit the mutual diffusion at interface region at 150°C, and the growth speed of intermetallic compound (IMC) decreased with the increase of Fe concentration. When stored at 200°C, the thickness of IMC would reach a limitation for all these three films after 4 days, and cracks occurred at the interface between IMC and Fe-Ni layer. Temperature cycling tests revealed that SnAgCu/Fe-50Ni solder joint had the lowest failure rate (less than 10%), which has the best interfacial reliability among three compositions.

Key words

Fe-Ni alloy, UBM, IMC, Reliability, High temperature storage, Temperature cycling

I. Introduction

Accompanying the fast development of lead-free soldering in microelectronic industry, traditional under bump metallization (UBM) materials such as copper and electroless nickel are consumed quite quickly due to the higher reflow temperature of lead-free solders than that of SnPb solders [1-4]. On the other hand, solder joints are getting smaller due to the increased package density [5,6]. Therefore, advanced high density packaging process like chip scale packaging (CSP), is facing new challenges of interfacial reaction and reliability issues [7-9].

As it had been reported before, Fe-Ni alloy exhibits a much slower interfacial reaction rate than that on traditional UBMs using typical Pb-free solders [10], and the shear strength of SnAgCu solder joint could be slightly improved by replacing the Cu/Ni UBM with the Fe-Ni UBM [11]. Moreover, with adequate pre-treatment during soldering, the wettability of Fe-Ni UBM is also quite acceptable [12]. Thus Fe-Ni alloy is a good candidate as novel UBM materials, which has not been industrialized yet. In this study, the interfacial reliability of SnAgCu/Fe-Ni solder joints was tested by high temperature storage, temperature cycling, and ball shear tests, and all of the test methods were complying with the requirement of JEDEC standards.

II. Experimental procedure

Fe-Ni UBM films were deposited with a customized 8-inches wafer electroplating system with detailed compositions of the plating bath as described before [13]. The concrete parameter of wafer plating was as follows: 1.5A/dm^2, 50°C, 10min, pH=2.2. Different content of Fe in the deposit was regulated by adding different amounts of Fe^{2+} to the plating bath, and three types of Fe-Ni UBM had been prepared which were separately Fe-75Ni, Fe-50Ni and Fe-30Ni in thickness of about 1μm. After the plating process of Fe-Ni UBM, three pieces of wafer had been experienced the following process of photoresist removing, Cu etching, solder ball planting and lead-free reflowing. Sn98.5Ag1Cu0.5 (SAC105) solder balls in diameter of 300μm were reflowed at about 250°C for two minutes.

Table 1 Temperature cycling text condition

Cycling region	Heating rate	Cooling rate	Soaking time	Cycling times
-40℃~+125℃	11℃/min	11℃/min	7.5min	640 (20 days)

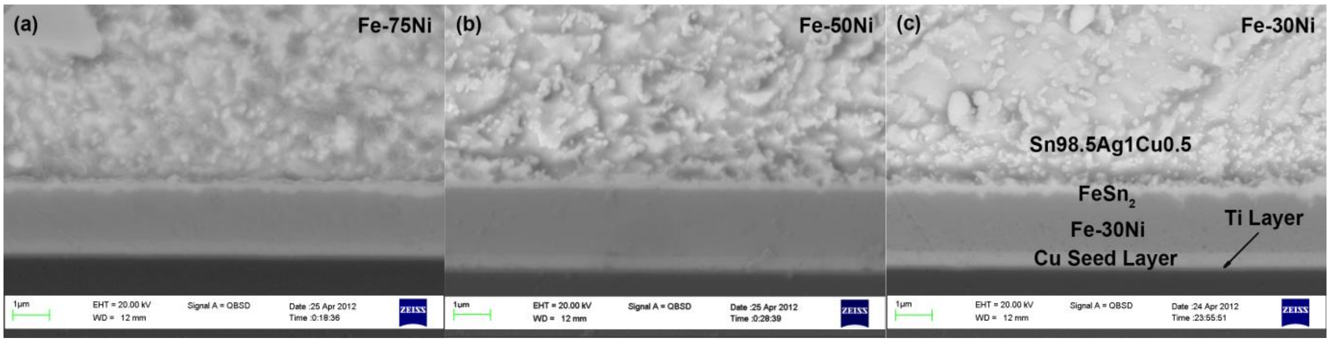

Fig.1 Interfacial morphology of different Fe-Ni UBM barrier layers after reflow (a) Fe-75Ni, (b) Fe-50Ni, and (c) Fe-30Ni

The packaged wafer was separated into square pieces (10mm×10mm) by precise wafer cutter and each piece had approximately 400 solder balls. High temperature storage (HTS) tests at 150, and 200°C were designed according to JEDEC-22A103D standard, considering the storage time, experiment cost, as well as the accelerating effect during extra high temperature. The condition of temperature cycling (TC) was listed in Table 1, which was selected according to JEDEC-22A104D standard. Tested SAC105/Fe-Ni joints were sampled respectively after 1d, 2d, 5d, 7d, 10d, 15d and 20d and a statistic analysis on the destruction rate of joints was performed accordingly.

After different testing the scanning electron microscope (SEM) samples were sealed in transparent epoxy resin, and were ground with sand paper of 400#, 1200#, 2000# in sequence from the sample surface. Then the samples were polished by polishing solution with 0.05μm particle in diameter until the SAC/Fe-Ni interface could be clearly seen by optical microscope and the scratch on Si substrate almost disappeared. Before observation with SEM, Nitric Acid-95% Alcohol solution had been utilized to etch the SAC/Fe-Ni interface for nearly 5s. Detailed interfacial microstructure of HTS samples were characterized by LEO Supra35 field-emission SEM with a resolution down to tens of nanometers, while the collecting of statistic data of TC samples was performed on a Quanta 600 SEM with an ample room of specimen chamber for more samples. Both electron microscopes were equipped with an energy dispersive X-ray spectroscopy (EDS) system for compositional analysis.

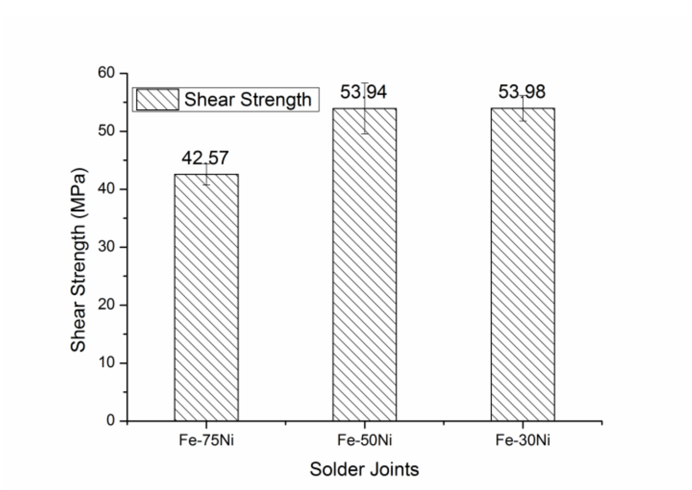

Fig.2 Ball shear test result on as-reflowed SAC/Fe-Ni solder joints

III. Results and discussion

3.1 Ball shear tests on as-reflowed solder joint

Fig. 1 exhibited interfacial microstructure of three kinds of as-reflowed SAC105/Fe-Ni joints in which (c) had been taken as an example to illustrate the layer structure. According to EDS analysis, a quite thin $FeSn_2$ layer had formed between all three kinds of Fe-Ni UBM and SAC105 solder balls after reflowing with the same technological condition. The thickness of $FeSn_2$ IMC on Fe-75Ni, Fe-50Ni, Fe-30Ni was 0.342, 0.338 and 0.256μm respectively, which decreased with the increase of Fe content in the Fe-Ni UBM. Besides, another isolated granular-like compound on $FeSn_2$ layer was only observed for SAC/Fe-75Ni interface after

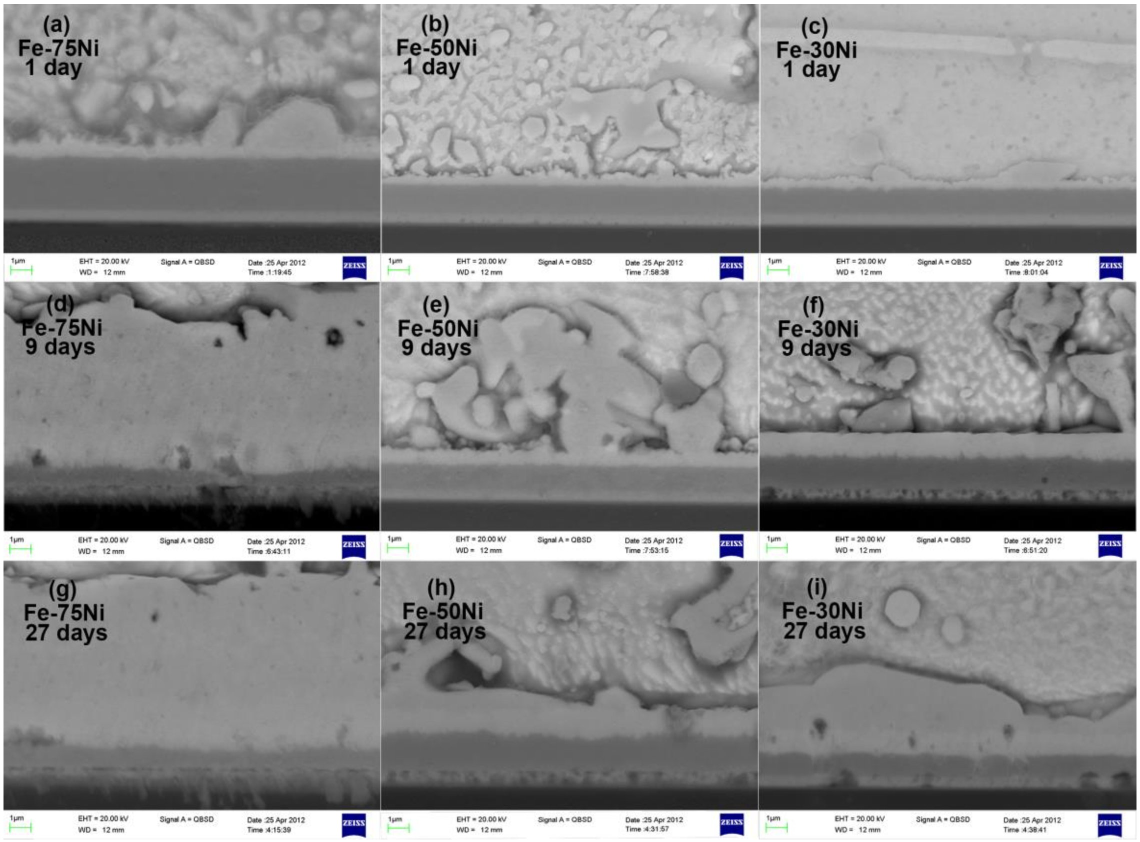

Fig.3 Interfacial morphology of different Fe-Ni solder joints after 1, 9 and 27 days' aging in 150°C. (a)~(c) 1 days, (d)~(f) 9 days, and (g)~(i) 27 days.

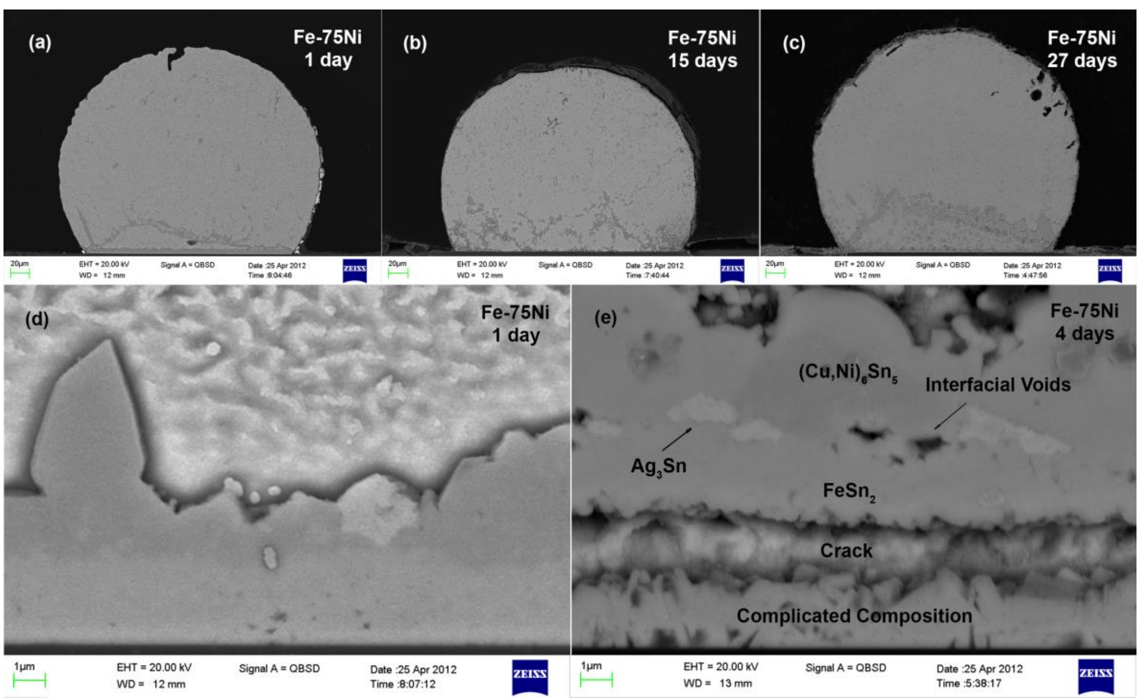

Fig.4 Interfacial morphology of Fe-75Ni solder joint after different days' aging in 200°C. (a) 1 days, (b) 9 days, (c) 27 days, (d) 1 day (microscopic morphology). (e) 4 days (microscopic morphology).

reflow, which could be described as CuNiSn (not strictly proportional chemical formula) according to the EDS analysis.

Ball shear test was conducted on as-reflowed solder joints with different Fe content, and the results were shown in Fig.2. The average shear strength of solder joints with Fe-75Ni, Fe-50Ni, Fe-30Ni UBM layer was 42.57, 53.94, 53.98 MPa respectively, showing an increase trend with higher Fe component in Fe-Ni plating. This result seems contradicting with the trend of wettability of Sn3.5Ag0.7Cu on Fe-Ni substrate [14]. It was reported that Fe-Ni plating with high Fe component had poorer wettability than that of lower ones, which was seemingly corroborated by perceptible sealing-off rate of actual high-Fe CSP samples [15]. Generally speaking, poor wettability has a direct relationship with inferior joint shear strength. However, in this work high-Fe concentration samples had the higher shear strength. This should be related to the conditions of IMC layer. The thinner the IMC layer and the straighter of the interface, the higher shear strength of the solder joints will be [16,17]. As SAC/Fe-30Ni interface possessed the thinnest IMC layer after reflowing, its highest shear strength was comprehensible. It should be noticed that the surface sealing-off rate could not be regarded as a strict wettability parameter, and average wetting angle is a more proper characterization data for wetting ability.

3.2 High temperature storage test

HTS experiments were executed at 150 and 200°C on three kinds of SAC/Fe-Ni joints, so as to simulate continuous thermal load in practical usage and investigate the interfacial evolution regularity under thermal field. Fig.3 shows the interfacial microstructure of these samples stored at 150°C for different days. Interfacial IMC of SAC/Fe-75Ni joints thickened extraordinarily after 9 days aging due to the formation and growth of CuNiSn or $(Cu,Ni)_6Sn_5$ outside of $FeSn_2$ layer. The interface between outer IMC and SAC105 solder was straight without interstate crack and spalling of entire layer as displayed in Fig 3(d). $FeSn_2$ layer at SAC/Fe-75Ni interface reached its limit thickness after 27 days storage as shown in Fig.3(g). However, SAC/Fe-50Ni and SAC/Fe-30Ni solder joints kept stable interfacial structure in which the thickness of $FeSn_2$ layer were only 0.91 and 0.74μm respectively after 27 days (see Fig.3(h) and 3(i)). Moreover, isolated granular-like CuNiSn compound generated at external side of $FeSn_2$ layer and formed a discontinuous and irregular IMC layer. Although outer CuNiSn IMC layer showed an inclination of spalling as aging time extended, entire-layer spalling could not be seen as shown in Fig.3(h) and 3(i).

When stored at 200°C, The interfacial IMC in all three kinds of samples displayed a rapid thickening in relatively short time period. For instance, after storage for 1 day part of the interfacial IMC of SAC/Fe-75Ni joint spall as an entire layer and drilled to the internal part of solder ball as shown in Fig.4(a). The thickness of $FeSn_2$ layer in SAC/Fe-75Ni joint had reached 2μm after 1 day and the Cu seed layer could not be clearly distinguished in the enlarged image of Fig.4(d), which demonstrated that atoms at 200℃ had the ability of full mutual diffusion in a fairly short time, thereby caused a tendency of composition unification in each layer. Fig.4(e) shows the detailed morphology of SAC/Fe-75Ni joints after 4 days storage under 200°C The former $FeSn_2$ layer had experienced a sufficient growth to 2-3μm thick, and a transverse crack was formed between it and substrate with a zigzag interface morphology. Massive scallop-like $(Cu,Ni)_6Sn_5$ layer was formed on $FeSn_2$ layer, and interfacial voids could be observed between those two layers. The drifting of outer IMC seems started, and the composition of bottom Cu seed layer had already transformed into a Sn-rich complicated one. It implies that the normal interfacial structure of SAC/Fe-75Ni had been seriously destructed after aging for 4 days at 200°C. After 9 days' storage at 200°C, spalling of huge granular or lamellar IMC with diameter of 10μm could be observed in solder ball near $(Cu,Ni)_6Sn_5$/SAC interface as shown in Fig.4(b). While 27 days later, interfacial IMC layer had completely spalled and drifted to internal part of solder ball (Fig.4(c)). The same situation occurred at SAC/Fe-50Ni and SAC/Fe-30Ni interface, which means that the diversity of Fe composition had no effects on the interfacial reaction in SAC105/Fe-Ni solder joints at a temperature as high as 200°C.

3.3 Temperature cycling test

SEM examination was used to statistically evaluate the incidence rate of interfacial crack, and the morphology of two typical cracks after TC test were shown in Fig.5. Crack initiated and propagated at Cu(Ti)/Si interface in most tested samples, which would eventually result in transverse fracture along the interface as shown in Fig.5(a) and (c). Moreover, quite a portion of cracks generated in Si substrate right beneath the solder ball and was in the shape of crescent as it could be seen in Fig.5(b) and (d).

The statistical data of interfacial damage was listed in Table 2. The numbers before "/" represent amounts of balls with cracks along the interface, while numbers after "/" represent total amounts of statistical samples and numbers in "()" represent amounts of balls with Si substrate cracks. It can be seen from Table 2 that SAC/Fe-75Ni joints exhibited an obviously destruction tendency only after 32 cycles, and the incidence of joints destruction had already reached 68% after 640 cycles. SAC/Fe-30Ni joints showed a relatively high inclination of cracks in Si substrate, which might release

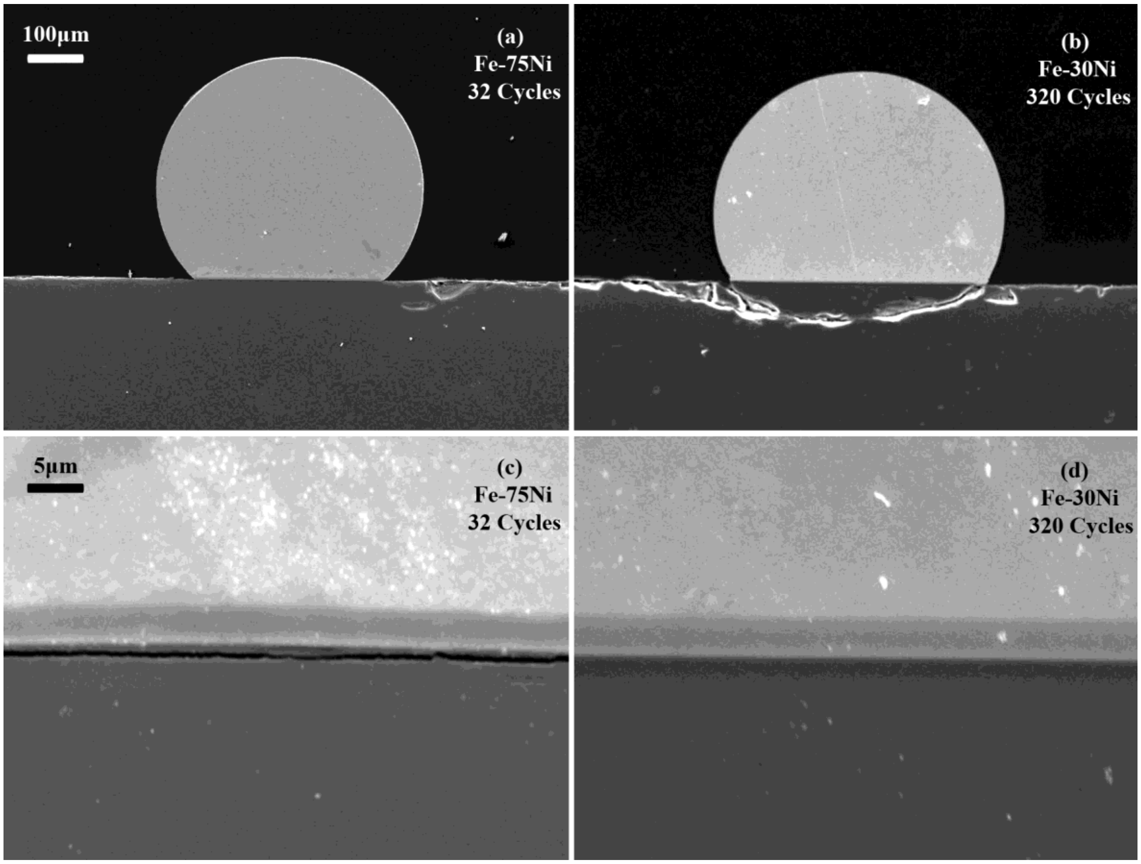

Fig 5 SEM image of interfacial cracks caused by temperature cycling. (a) and (c) Fe-75Ni solder joint after 32 cycles, (b) and (d) Fe-30Ni solder joint after 320 cycles.

interfacial thermal stress concentration so as to decrease the thermal cracking tendency at interface. The failure rate of SAC/Fe-50Ni solder joint was lowest with a destructive rate less than 10% including both types of cracks, which shows the best interfacial reliability among three compositions. It should be pointed out that as the tested CSP sample

Table 2 Statistical analysis of interfacial crack after different cycles of TC test

Cycles/Samples	Fe-75Ni	Fe-50Ni	Fe-30Ni
32	5/24	0/24	2/25 (1)
64	3/22	0/16	2/20 (2)
160	10/25	1/19	2/19 (2)
224	17/26	2/12 (1)	1/19 (5)
320	13/25	1/25	0/22 (3)
480	15/24	1/25 (3)	1/20 (3)
640	17/25	2/20	2/24 (5)

(10mm*10mm) had almost 400 solder balls and only 20-25 solder balls were observed cross-sectionally, more samples should be investigated to improve the representative of thermal cycle reliability of Fe-Ni/SAC interface.

III. Conclusion

1) After reflow the SAC/Fe-75Ni solder joint had the thickest layer of $FeSn_2$ IMC, on top of which there existed granular-like CuNiSn IMC. The shear strength for Fe-75Ni, Fe-50Ni, and Fe-30Ni reflowed solder joints were 42.57, 53.94, 53.98 MPa respectively, which are all satisfied with the requirement of industrialization (＞34.3 MPa).

2) During high temperature storage at 150°C, Fe-75Ni films (1μm thick) exhibited an obvious IMC growth (up to 10μm thick) after 9 days' aging, while Fe-50Ni and Fe-30Ni films could endure 27days' aging with less consumption of Fe-Ni layer. When stored at 200°C, Fe-75Ni, Fe-50Ni and Fe-30Ni film would reach the growth limit of $FeSn_2$ (2.2, 2.6, 3.3μm, separately) within 4 days, and the thickness limit of $FeSn_2$ layer increased with the increasing of Fe composition in the deposit.

3) During temperature cycling, a large amount of cracks could be observed at the Ti/Si interface of SnAgCu/Fe-75Ni solder joints with a destructive rate of about 20~40%. Fe-30Ni solder joint exhibited a small amount of arcuate cracks under Ti/Si interface, while less cracks could be discovered on Ti/Si interface. Fe-50Ni solder joint had relatively better reliability than other two compositions, and the destructive rate of both cracks was less than 10%.

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