Design and Process Optimization for Dual Row QFN

Danny V. Retuta, B.K Lim, H.B. Tan
United Test & Assembly Center Ltd (UTAC)
5 Serangoon North Ave 5, Singapore 554916
retuta_danny@sg.utacgroup.com, (+65) 65511591

Abstract
The continuous advancement in technology and miniaturization of electronic components, hand held and communication devices require superior thermal-electrical performance and miniature packages. An advanced and complicated Integrated Circuit (IC) device often demands increase in number of I/O's while maintaining its small size, footprint and weight. Dual Row Quad Flat No lead (DR-QFN) is an ideal solution for such demanding applications; however, despite the simplicity of its package structure, it possesses challenges in various assembly processes. This paper describes the problems that are associated with the different concepts of both 'saw' and 'punch' singulated DR-QFN and the corresponding solutions to overcome the barriers.

Lead isolation or separation of 1st and 2nd row of leads has always been the major challenge for saw singulated DR-QFN (DR-QFN-S) where solder burr and leadfinger delamination are inherent. Shorting between inner and outer leads during SMT is also apparent. This paper demonstrates the study on different leadframe designs and how the solutions were derived. Through modeling, the impact on solder joint reliability for the different leadframe design and the respective surface mount behavior was also explored.

The primary focus in designing punch singulated DR-QFN (DR-QFN-P) is to do away with lead isolation, which is to maintain its simplicity and cost effectiveness. The key factor is the design of the leadframe and the etching capability of the manufacturer. But despite the absence of lead isolation process, DR-QFN-P similarly comes with challenges such as solder bridging and lead-to-lead short. Further in this paper describes the approach taken to overcome issues associated with this package.

1.0 Introduction
Consumers nowadays are getting particular not only on the functionality and cost of electronic gadgets but also with their size and weight. This fast pace trend in technology demands innovative and cost effective packaging solutions. Moreover, the emergence of sophisticated functionality in IC devices requires more than just by shrinking the package but it also calls for drastic increase in I/O density. QFN package, despite its small size, is not exempted from the challenge and this is where Dual Row or Multi Row leads came into existence.

As the name implies, DR-QFN features two rows of leads and caters more I/O’s than a conventional single row QFN. It can equal or even exceed the pin count of a relatively bulky QFP package. A 12x12 QFP 80L for example can be shrunk into 76L 7x7 DR-QFN or 92L 8x8 DR-QFN.

Assembly houses that took part in bringing DR-QFN into reality raced towards different directions depending on their available resources and infrastructures. Most players focused on leadframe design and process development be it ‘punch’ or ‘saw’ singulated while others took a step ahead by developing a non-standard assembly process than can even go beyond two rows.

Figure 1 shows how a typical DR-QFN differs from a conventional QFN. The increase in pin count is shown in Table 1.

<table>
<thead>
<tr>
<th>Package Size</th>
<th>Convnetional QFN</th>
<th>Dual Row QFN</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x4</td>
<td>28L</td>
<td>-</td>
</tr>
<tr>
<td>5x5</td>
<td>32L</td>
<td>44L</td>
</tr>
<tr>
<td>6x6</td>
<td>40L</td>
<td>60L</td>
</tr>
<tr>
<td>7x7</td>
<td>48L</td>
<td>76L</td>
</tr>
<tr>
<td>8x8</td>
<td>56L</td>
<td>92L</td>
</tr>
<tr>
<td>9x9</td>
<td>64L</td>
<td>108L</td>
</tr>
<tr>
<td>10x10</td>
<td>72L</td>
<td>124L</td>
</tr>
<tr>
<td>12x12</td>
<td>88L</td>
<td>156L</td>
</tr>
<tr>
<td>13x13</td>
<td>96L</td>
<td>172L</td>
</tr>
</tbody>
</table>

Figure 1: Comparison between conventional 7x7 QFN and 7x7 DR-QFN.
2.0 Challenges for DR-QFN

2.1 DR-QFN-S (Saw Type)

As mentioned, lead isolation is the biggest challenge for this package where quality issues and reliability treats involved seem inevitable. During the early stage of DR-QFN development in UTAC, excessive solder burr and solder bridging (see figure 2.1.2) showed up instantly and this is where development evolved. Efforts to overcome these issues focused on the leadframe design particularly on the connecting metal (the one holding both inner and outer leads) or ‘lead dambar’ where lead isolation takes place.

The position of half-etch along the connecting metal or lead dambar was first understood. The initial design, shown in Figure 2.1.1, was half-etched on the top as illustrated in option 1 of figure 2.1.3. This option is susceptible to solder bridging/burr due to the large amount of exposed metal being cut during isolation. The 2nd option shown in Figure 2.1.3 could have been a straightforward solution for solder burr but the risk of hitting the wires connected to the outer leads is relatively high. There’s not much margin to work at for the outer wires as the terminal pitch between inner and outer leads is only 0.50mm and the distance is only 0.20mm.

Another major issue associated to lead isolation process is the leadfinger delamination as pictured in Figure 2.1.4. This time zero phenomenon is an indication of high stress applied to the leads during the cutting or isolation process. The adhesive strength between the mold compound and leadfinger, which in this case is plated with silver, cannot withstand the mechanical stress coming from the rotating resin bonded blade.

Another potential issue related to the structure of this package is the shorting of solder between the two rows of leads during board mount (see illustration in figure 2.1.5). During lead isolation, a small portion of both outer and inner leads are being cut creating a sidewall of copper. The solder is then allowed to wet onto the sidewall forming a full solder fillet at the toe region.

The governing JEDEC standard for dual row or multi row at early stage of DR-QFN-S development is indicating an inner and outer terminal pitch of 0.50mm which is indirectly suggesting using 0.20mm isolation blade to attain a nominal lead length of 0.30mm. This requirement leaves very tight process margin for such package requiring lead isolation.

2.2 DR-QFN-P (Punch Type)

Lead isolation is not the right way to go for punch singulated QFN, as the structure of the package does not have the leeway for such process. One of the prominent features of punch type is its flange and this is one reason why inclusion of isolation trench is not recommended due to its susceptibility to crack and chip-out. Furthermore, the volume of unnecessary copper to be cut can be awfully huge and hence make the blade life ten-fold shorter and unit cost will shoot up exponentially.

The widely used concept for punch type DR-QFN is the staggered lead design shown in figure 2.2.1. The inner and
outer terminals are interconnected through the dambar that is outside the package outline. The inner leads are connected to the dambar by means of a thin half-etched copper that runs in between the two outer leads.

![Figure 2.2.1: Typical staggered lead design](image)

The key to a well-designed leadframe lies on the etching capability of the frame manufacturer. For 0.20mm thickness, it’s difficult to meet 0.50mm terminal pitch due to the tight metal-to-metal distance between the staggered leads. This is not a concern for 0.65mm pitch as there is enough space but the number of leads will be reduced significantly (see table 1 for comparison in leadcount between 0.50 and 0.65).

To meet 0.50mm pitch, the leadframe thickness has to be reduced to 0.15mm to meet the etching design rules established by the leadframe makers. The leadframe can become a bit flimsy though, so if handling is a concern then there are alternative copper materials like C7025 that can be used to maintain the stiffness.

The challenge for 0.50mm pitch DR-QFN-P does not end on the leadframe design; there are design related issues that need to be addressed as well. One foreseen issue that can happen during solder plating is the shorting of leads on top flange caused by the potential bridging of solder between the outer lead and the intermediate bar of the inner lead. See illustration in Figure 2.2.2.

![Figure 2.2.2: Potential solder bridging issue for 0.50mm pitch](image)

Two other problems encountered for 0.50mm pitch that need to be dealt with include:

1) Lead-to-lead short on top flange caused by the spread out of solder during package singulation. The photo of the actual unit is shown in figure 2.2.3. The fanning out of solder is the effect of supporting the package, by the singulation die, during cutting process. This is inherent to dead-bug singulation and something that cannot be avoided.

2) Incomplete fill/mold at the dambar area as pictured in Figure 2.2.4. This issue is a clear manifestation of space congestion as a result of reducing leadframe thickness and drastic increase in number of leads.

![Figure 2.2.3: Lead-to-lead short at singulation](image)

![Figure 2.2.4: Incomplete fill problem for 0.50 pitch](image)

### 3.0 Design and Process Optimization

#### 3.1 DR-QFN-S

The approach taken to overcome barriers at isolation process focused on the leadframe design. The hypothesis is, minimizing the amount of metal along the isolation line will likewise minimize solder burr and lessen the stress on the leadfinger that causes delamination. Four different designs as illustrated in figure 3.1.1 were tooled-up and evaluated to validate hypothesis. All the 4 designs were half-etched on topside as shown in option 1 of 2.1.3. Type 1 is a simplified design wherein the inner and outer leads are connected only through an in-line connecting bar. Type 2 is still following the concept of the original design except that the half-etch on the lead dambar was made wider than the isolation blade. Having 0.25mm half-etch width (or 50µm wider than the blade), type 3&4 are expected to have less stress on the leads as it’s being cut only on the half-etch region. Type 1&2 has only 0.15mm wide half-etch and therefore the 0.20mm blade is cutting some portions of the active leads resulting additional stress and Cu smear at the valley of the isolation trench.
The four leadframe types were evaluated comparatively and results are shown in Table 3.1.2. Both type 2&3 with a dambar width two-third less than the original design showed encouraging improvement in terms of solder burr. Type 1 on the other hand displayed the most favorable result validating the hypothesis that the level of solder burr is proportional to the metal density along the isolation line. Type 3&4 as expected did not show any indication of Cu smear at the valley or bottom of the isolation trench. In summary, none of the 4 designs exhibited capability to address all the issues; nonetheless a formula can be derived from this evaluation to achieve the desired outcome. From the table (3.1.2), we can tell that Type 1 lead design combined with wide half etch of Type 3 or 4 will result good isolation quality. Figure 3.1.3 shows the cutting quality of Type 1 and 3.

However, leadfinger delamination remains an issue as all the designs still manifested the same phenomenon observed on the original design.

**Table 3.1.2: Summary of evaluation results**

<table>
<thead>
<tr>
<th>LF Design</th>
<th>Solder Bridging</th>
<th>Solder Burr (Btm of Trench)</th>
<th>Cu Smear (After Isolation)</th>
<th>CSAM (After Isolation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>✔ ✔ ✔</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Type 2</td>
<td>✔ ✔</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Type 3</td>
<td>✔   ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✗</td>
</tr>
<tr>
<td>Type 4</td>
<td>✗  ✗ ✔</td>
<td>✗ ✔</td>
<td>✗ ✔</td>
<td>✗</td>
</tr>
</tbody>
</table>

- ✔ - Good, ✔ ✔ - Very good
- ✗ - Bad, ✗ ✗ - Very Bad

Further study was conducted to tackle barriers and this time the aforementioned potential board level issue was taken into consideration. When JEDEC released DR-QFN standard indicating a terminal pitch of 0.75mm between inner and outer leads, it opened wider process margin to work at and created more flexibility on process and design.

To meet the new pitch requirement, the distance between the two rows of exposed leads must be around 0.45mm apart suggesting that the isolation blade has to be 0.25mm wider than the previous one. Another approach is to use the same 0.20mm isolation blade but the half-etch has to be positioned at the bottom side to maintain the required lead length and terminal pitch. However, for this concept the depth of isolation cut must be more than the thickness of leadframe and as previously discussed this will put the outer row wires into imminent danger. Nonetheless, the increase in terminal pitch created some options to overcome the risk and one of which is by optimizing the loop profile for the outer wires. Increasing the approach angle and adding a kink near the 2nd bond can increase the clearance between the wire and the bottom of the isolation trench. See illustration in Figure 3.1.4.

One idea that came out to get rid of all the lead isolation issues is to do away with lead isolation process itself. Why not adapt the concept of punch type DR-QFN where the leads are arranged in staggered manner and lead isolation is done during the package singulation?

Three new leadframe designs were again drawn and manufactured for testing (see figure 3.1.6 for illustration). Type 5 is a hybrid design of type 1 and 3 (the isolation cut is wide and shallow), while Type 6 is a new concept that is designed to completely eliminate solder burr problem (the cut is deep and narrow). Incorporated also into Type 5&6 design is the enhancement in the interlock feature of the leads as shown in figure 3.1.5. This aims to strengthen the grip of the leads and prevent delamination during isolation process. The exposed lead width was reduced from 0.30mm to 0.20mm in order to make room for additional 50um onto the half-etched interlock region.

![Figure 3.1.4: Outer wire optimized looping profile.](image)

![Figure 3.1.5: Cross section view of a lead showing the enhancement in interlock feature.](image)
The three new leadframe designs were evaluated in the same manner as the first four types where processability, quality and reliability are the main considerations. All the quality issues at lead isolation process were addressed on Type 5 & 6 however leadfinger delamination is still evident, though the severity and failure rate had improved dramatically (see comparison in figure 3.1.8). Between Types 5 & 6, no significant difference seen in the extent of delamination but the latter has much less units affected. An attempt to optimize spindle speed and feed rate for Types 5 & 6 also did not indicate positive result. The said parameters were varied from 10-40Krpm and 5-30mm/sec respectively but the SAT results did not show any direction that will lead to the resolution of leadfinger delamination.

Type 7 is by far the design that showed the most favorable result be it in quality or reliability. All the issues inherent to the isolation process were eliminated and likewise the risk of having lead-to-lead short at SMT is minimized due to the elimination of fillet formation highlighted in Figure 2.1.5.

Table 3.1.7: Summary of results.

<table>
<thead>
<tr>
<th>LF Design</th>
<th>Solder Bridging</th>
<th>Solder Burr</th>
<th>Cu Smear (Bsub of Trench)</th>
<th>CSAM (After Isolation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 5</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Type 6</td>
<td>na</td>
<td>na</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Type 7</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>✔</td>
</tr>
</tbody>
</table>

✔ - Good, ✔ ✔ - Very good
✗ - Bad, ✗ ✗ - Very Bad
na - Not applicable or not affected.

With all the positive results seen on Type 7, it was eventually selected as the leadframe design for DR-QFN-S. This leadframe design does not only address numerous issues but also simplifies the process and reduce assembly cost by eliminating non-value added lead isolation process. The package has undergone full reliability assessment and it passed both electrically (open/short) and SAT (see figure 3.1.8). It also passed MSL2@260°C without any delamination.

3.2 DR-QFN-P (Punch Type)

Punch singulated DR-QFN may appear less complicated than its ‘saw type’ counterpart but the issues described in section 2.2 require complicated solutions.

One approach to settle all the issues for 0.50mm pitch is to come up with a mold cavity bar having a ‘flange overmold’ feature. The purpose of this enhancement is to cover the exposed copper on top side of flange with mold compound and at the same time create a relief for mold compound to flow through the dambar area. Shown in figure 3.2.2 is the design of the cavity bar with flange overmold feature while the eventual structure of the package is shown in figure 3.2.3.

This concept was proven to be an excellent solution to all the quality problems, it also demonstrated remarkable reliability performance, but there are some disadvantages that need to be considered especially when used for mass production. For one, mold tooling is non-standard and thus it will be dedicated to DR-QFN-P and cannot be shared with the conventional QFN or vice versa. Singulation process will also
face the same dilemma, the additional step on the cavity will require custom-made cutting die, which is likewise not applicable for conventional QFN. Tooling investment, machine conversion, spare parts maintenance and additional process control are also some of the utmost concerns.

UTAC came up with a more practical solution to overcome hindrances on DR-QFN-P by simply re-designing the leadframe. The effect of having overmolded flange can also be achieved by half-etching the top portion of the outer leads around the flange area as shown in figure 3.2.4. As a result, the half etched portion will be overmolded leaving only the intermediate bar of the inner leads exposed on top of the flange (see illustration in figure 3.2.5). The distance between the exposed metals is now more than enough to eliminate the risk of having both solder bridging and lead-to-lead shorting caused by solder spread out. The inclusion of half-etch also addressed incomplete fill problem by acting as channel for the mold compound to flow towards the dambar area.

This simple yet effective solution also satisfied the objective of consolidating standard tooling for QFN whether it’s single or dual row. Mold tooling for conventional QFN can be used for DR-QFN-P; only a minor change in cull block thickness is necessary to cater 0.15mm leadframe thickness. It is also 100% compatible with the existing punch singulation tooling; therefore no additional investment or conversion is required.

4.0 Board-level T/C solder reliability study
While DR-QFN packages share common characteristics with conventional QFNs in terms of design, performance and reliability [1-3], surface mounting stands out as a major challenge in the package development. As indicated previously, inner and outer leads of DR-QFN-S are susceptible to shorting due to space constraint. It becomes necessary to optimize the solder interconnect formation both to minimize the risk of shorting and to maintain adequate board-level reliability especially under temperature cycling.

Shown in figure 4.1 is a summary comparing typical board solder formation for different DR-QFN packages (saw-type). The main differences between these options include: presence of pull back and non-pull back lead design, choice of leadframe material and thickness. Non-pull back lead design permits the formation of full solder fillet at the toe region, allowing solder to wet onto the sidewall of the lead. Full fillet formation is however not guaranteed due to the lack of solder plating on the sidewall. For analysis purpose, full solder fillet at the toe region will be considered for non-pull back lead design. Type 7 design requires no lead isolation but requires a thinner leadframe of 0.15mm in line with the etching capability of leadframe supplier.
Finite element analysis (FEA) has been used to study the effects of structural designs (Type 5, 6 & 7) on board-level solder fatigue reliability under temperature cycling condition. Solder joint damage in the form of fatigue cracking has been widely reported to remain the prime cause of failure under board level temperature cycling. Solder cracking is associated with the thermal expansion mismatch of the package and PCB materials, resulting in fatigue straining within the solder interconnect. As a benchmark, 62Sn/36Pb/2Ag eutectic solder material will be referenced for the current study. A three-dimensional half strip model has been constructed which aims to provide adequate geometrical representation of the inner and outer leads (as well as the neighboring structure) without extensive computational time (refer to figure 4.2). Geometrical land pads on the PCB are designed based on internal guideline for QFN board mounting. In accordance to typical board-level T/C condition, the model is subjected to a temperature cycling condition of -40°C to 125°C, with 15 minutes ramp and dwell at 1 cycle per hour. Darveaux’s [4] viscoplastic solder constitutive model has been adopted for the current solder fatigue analysis. The accumulated energy density (volume averaged) per cycle has been used as damage representation for solder fatigue analysis.

As part of the cause findings, it is observed that large shearing occurs near the toe of the inner lead and heel of outer lead for type 6 and type 7, in which the leads are pull back in design. On the other hand, full fillet formation resulting from a non pull back lead design (Type 6) redistributes shear loading especially at the lead corner giving rise to a multi-axial straining at lower intensity (refer to 4.4). For type 7, it is also observed that though a thinner leadframe yields limited increase in energy density, a corresponding change to stiffer C7025 leadframe material from C194 aggravates expansion mismatch between the package and the PCB, resulting in higher plastic deformation.
As part of validation, actual board level T/C test with ‘daisy chain’ monitoring has been incorporated into the overall DR-QFN package development, together with surface mounting evaluation to address the risk of leads electrical shorting. Testing is in progress at the time of publication and will be discussed in future publication. Surface mounting guidelines for DR-QFN packages will also be released in subsequent reports.

**Conclusion**

The series of evaluations conducted on DR-QFN-S revealed that lead isolation is not recommended due to its susceptibility to a number of quality and reliability issues. Using staggered lead design as solution to the problems does not only guarantee a more robust and reliable package but it also simplifies the assembly flow and reduce unit cost as a result.

As for punch type DR-QFN, this paper described a couple of proven and effective ways to overcome challenges on 0.50mm pitch such as leadframe design improvement and tooling modification. However, for dynamic assembly subcontractors like UTAC where machine and tooling flexibility are important, the latter may not be the recommended solution to go into. Focusing on the leadframe design and leveraging on the capability of the frame manufacturer can simplify the solution and prevent unnecessary investment. Also, a number of tangible advantages can be gained from using the enhanced leadframe design described in this paper.
Acknowledgments

We, the authors, would like to acknowledge UTAC management for the guidance and support during the development of this project. We would also like to extend our gratitude to all the PAT engineers, EA’s and Design engineers who helped make this project a success.

References


